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Massachusetts Institute of Technology

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AN INVESTIGATION OF TOTAL DETONATION OPERATION OF A CARBURETOR-SUPPLIED INTERNAL COMBUSTION ENGINE

RALPH EARL BARNARD
FRANK GILLILAND

Thesis
B228

U. S. Naval Postgraduate School
Monterey, California

[illegible] '57
[illegible]

AN INVESTIGATION OF TOTAL DETONATION OPERATION OF A CARBURETOR-SUPPLIED INTERNAL COMBUSTION ENGINE

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B. S., U. S. Naval Academy, 1946

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Submitted to the
Department of Naval Architecture and Marine Engineering
on May 15, 1952,
in Partial Fulfillment
of the Requirements for the
Degree of Naval Engineer

I ABSTRACT

Title of Thesis : An Investigation of Total Detonation
Operation of a Carburetor-Supplied
Internal Combustion Engine.

Names of Authors: Ralph E. Barnard
Frank Gilliland

Submitted to the Department of Naval Architecture and Marine Engineering on May 15, 1952, in partial fulfillment of the requirements for the degree of Naval Engineer.

The authors have carried out an investigation of the operation of a single-cylinder CFR engine employing the total detonation cycle. In this cycle, constant volume combustion is realized when the very rapid combustion occurs at top dead center in the engine cycle. By virtue of this fact the cycle permits greater cyclic efficiency than the conventional spark ignition engine wherein the combustion occurs over a considerable portion of the engine cycle. Normal heptane reference fuel having an octane rating of 0 was used throughout the study. A photo-multiplier tube was used to measure the position in the engine cycle of the various events in the detonation phenomena. This was accomplished by looking into the combustion chamber through a quartz window installed in a spark plug recess. The output of the photo-multiplier tube plotted against crank angle shows marked similarity to the pressure-crank angle diagram of the engine operating on this cycle. No electrical ignition system was used to initiate combustion--this being accomplished by raising

19140

the compression ratio until the mixture autoignited.

The major part of the data was taken with atmospheric inlet and exhaust pressures and an inlet fuel-air charge temperature of 170F. The compression ratio of the engine was varied from 6.0 to 8.5 and the speed of operation from 900 to 1500 rpm. It was found that the duration of the preflame reaction(the cool flame occurring just prior to the explosion of the fuel-air charge) and the crank angle at which it occurred in the cycle did not perceptibly affect the point of autoignition. The point of autoignition was found to be mainly a function of the inlet temperature and the compression ratio. The cycle shows high efficiencies over a considerable speed range, but a limited flexibility with regard to reduced inlet pressures; hence, practical engine application would at present be limited to constant load applications. The engine makes a loud knocking sound and this may further restrict its application. The effect on engine parts of such operation needs to be investigated.

The thesis is concluded with suggested further studies which are deemed necessary in the development of a practical engine using this cycle of operation.

Thesis Supervisor: William A. Leary
Title : Ass't. Prof. of Mech. Eng.

Cambridge, Massachusetts
15 May 1952

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled: "An Investigation of Total Detonation Operation of a Carburetor-Supplied Internal Combustion Engine."

Respectfully yours,

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Professor William A. Leary for his guidance and encouragement; to James C. Livengood for his helpful instrumentation suggestions; and to the entire staff of the Sloan Laboratory for their assistance and cooperation.

[illegible]

The author wishes to express [illegible] appreciation to Professor [illegible] for his [illegible] and encouragement, to [illegible] for his [illegible] suggestions and to the [illegible] of the [illegible] for their assistance in [illegible].

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II INTRODUCTION

An investigation of the possibilities of operating an internal combustion engine on the so-called "total detonation cycle" is the subject of this thesis. The total detonation cycle is an engine cycle in which, for all practical purposes, instantaneous combustion is realized. Thermodynamic analysis shows that when the combustion begins and is completed during the instant at which the piston is at the top of the working stroke, the efficiency and power output of an engine are maximum. In a conventional piston engine, spark ignition or diesel, the combustion is progressive and requires a considerable period of time, that is, by comparison with the speed at which the piston is moving. As a result of these time-consuming burning processes it is impossible for the conventional engines to realize the high efficiency inherent in the instantaneous combustion cycle, or as it is more generally called, the "constant-volume cycle." The term "constant-volume" means simply that the combustion occurs so rapidly that the piston motion may be considered negligible during the process, and hence the volume of the combustion chamber is constant.

Since this is a new field of investigation and a consistent nomenclature has not been developed, the following terms will be used to describe the phenomena. Refer to Figure 1 in conjunction with the following definitions.

Start of Preflame Reaction. That point in the cycle where the first visible radiation is given off from the fuel-air mixture. See A, Figure 1.

Duration of Preflame Reaction. The duration of the blue flame or low order light, expressed either in units of time or crank angle, which occurs between the start of the preflame reaction and the point of autoignition, sometimes called "blue-flame reaction" or precombustion reaction. This is shown as Z in Figure 1.

Point of Autoignition. The point in the reaction characterized by practically instantaneous or constant volume combustion. This point (B of Figure 1) is actually a small time interval rather than a single instant, but it is referred to as a point because of its very small duration. It is this extremely rapid combustion which gives rise to the shock wave which we hear as a "knock" in an internal combustion engine.

Detonation. The combination of the preflame reaction and the point of autoignition, shown in Figure 1 from A through B.

Total Detonation. This refers to a process where no spark plug or other device is employed specifically to ignite the fuel-air charge, as contrasted with the conventional automobile engine or diesel engine where a spark plug or glow plug is used.

It has been shown (Reference 2, 3, 5) that chemical changes in the fuel-air charge in the cylinder occur during the compression stroke of a motored engine. There is a slight increase in cylinder pressure when these so-called precombustion or preflame reactions start (Reference 6). If the compression ratio is high enough, autoignition or rapid constant volume combustion of the charge commences with the accompanying audible knock and high rate of cylinder pressure rise. This phenomenon has been shown on pressure-crank angle diagrams obtained by using the M.I.T. point by point pressure indicating equipment (Reference 6). A typical diagram is shown in Figure 1A.

A blue light, or as it has been called "cool flame," is given off from the fuel-air charge when the preflame reaction occurs. It is possible to detect this blue light radiation by using a sensitive photo multiplier tube circuit or a pressure-crank angle indicator (Reference 6). However, the phototube is superior to the pressure indicator with regard to identifying the exact crank angle at which the preflame reaction starts.

References 2, 3, 4, and 5 cover most of the work already completed in this field of investigation. Since this is a relatively new approach to the study of engine detonation, the available literature is quite limited. Active research

programs on the subject are now being pursued by the National Bureau of Standards and several motor fuel and chemical companies.

This study was made to determine the crank angle relations between the incidence of the preflame reaction and the point of autoignition, and their effects on the total detonation phenomena. With this information operating conditions can be regulated so that the point of autoignition or constant volume combustion can always be experienced when the piston is at top dead center.

The following is a description of the apparatus used to study the total detonation cycle.

Engine Set-up - Schematic diagram shown in Figure 7.

The test engine is a CFR engine located in the Sloan Laboratory at M.I.T. A direct current cradle-type dynamometer was used to record the brake mean effective pressure (bmep) of the engine. An ASME square-edged orifice with flange taps was used to measure the air flow to the engine. See Figure 31 for the air orifice calibration curve. The standard type of rotameter was used to measure the fuel flow. The rotameter calibration curve is shown in Figure 32. The auxiliary apparatus was conventional.

Recording Apparatus

No ignition system was used since the total detonation

cycle is a compression-ignition type of cycle. This condition eliminates the spark plug and permits it to be replaced by a quartz window unit as shown in Figure 7. In this manner it is possible to look into the combustion chamber during total detonation operation. The radiation in the cylinder passes through the quartz window into a light-tight blackened pick-up enclosure made of heavy brass tubing. For details of this unit see Figure 3. The spring suspension of this unit was designed to eliminate the vibrations set up by the total detonation operation in the cylinder, which might excite the pick-up enclosure. A short section of rubber tubing connecting the window holder to the pick-up enclosure is helpful in this respect and limits the heat transferred from the cylinder wall to the enclosure which houses the phototube. This design proved quite successful in eliminating any microphonics which are caused by such vibrations.

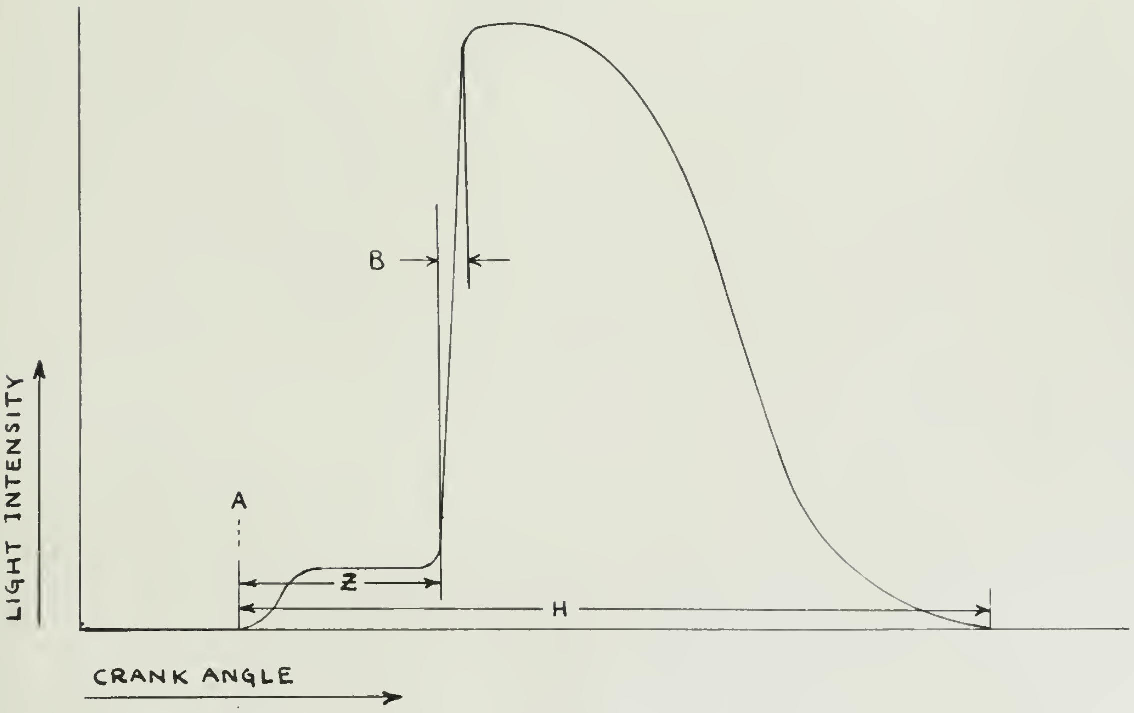
A variable negative direct current power supply of about one thousand volts maximum potential for the photo-multiplier tube circuit is obtained through a series combination of 67.5 volt batteries. Figure 2 shows the details of the photo-multiplier tube electrical circuit. The output of the phototube is fed into a Dumont 304-H cathode ray oscilloscope for observation. Figure 5 shows the synchronizing signal generator designed to synchronize the cathode ray

oscilloscope with the engine cycle.

A phasing device is used to determine the crank angle at which the preflame reaction and the point of autoignition occur. This device consists of a set of breaker points which can be rotated with respect to a cam on the engine crankshaft. The breaker points are placed in the circuit of an ignition coil and cause a small neon tube, mounted in a rotating disk on the crankshaft, to flash when the breaker points are closed. At the same time electromagnetic radiation from the spark plug causes a pip to be superimposed on the phototube pattern on the cathode ray oscilloscope. Thus by shifting the position of the breaker points with respect to the cam the pip can be made to coincide with any event in the phototube pattern. The crank angle at which this event occurs can be read from a stationary scale mounted at the circumference of the rotating disc containing the neon tube. With this arrangement the crank angle at which an incident occurs along the phototube output trace on the cathode ray oscilloscope screen can be read within ± 1 degree by matching the spark signal with the point of interest and reading the angle on the spark protractor. This accuracy is deemed adequate for this investigation. An M.I.T. strip camera was used to photograph the total detonation cycle events as shown on the oscilloscope screen. All electrical

leads and the power supply unit are shielded to prevent interference signals from distorting the scope trace.

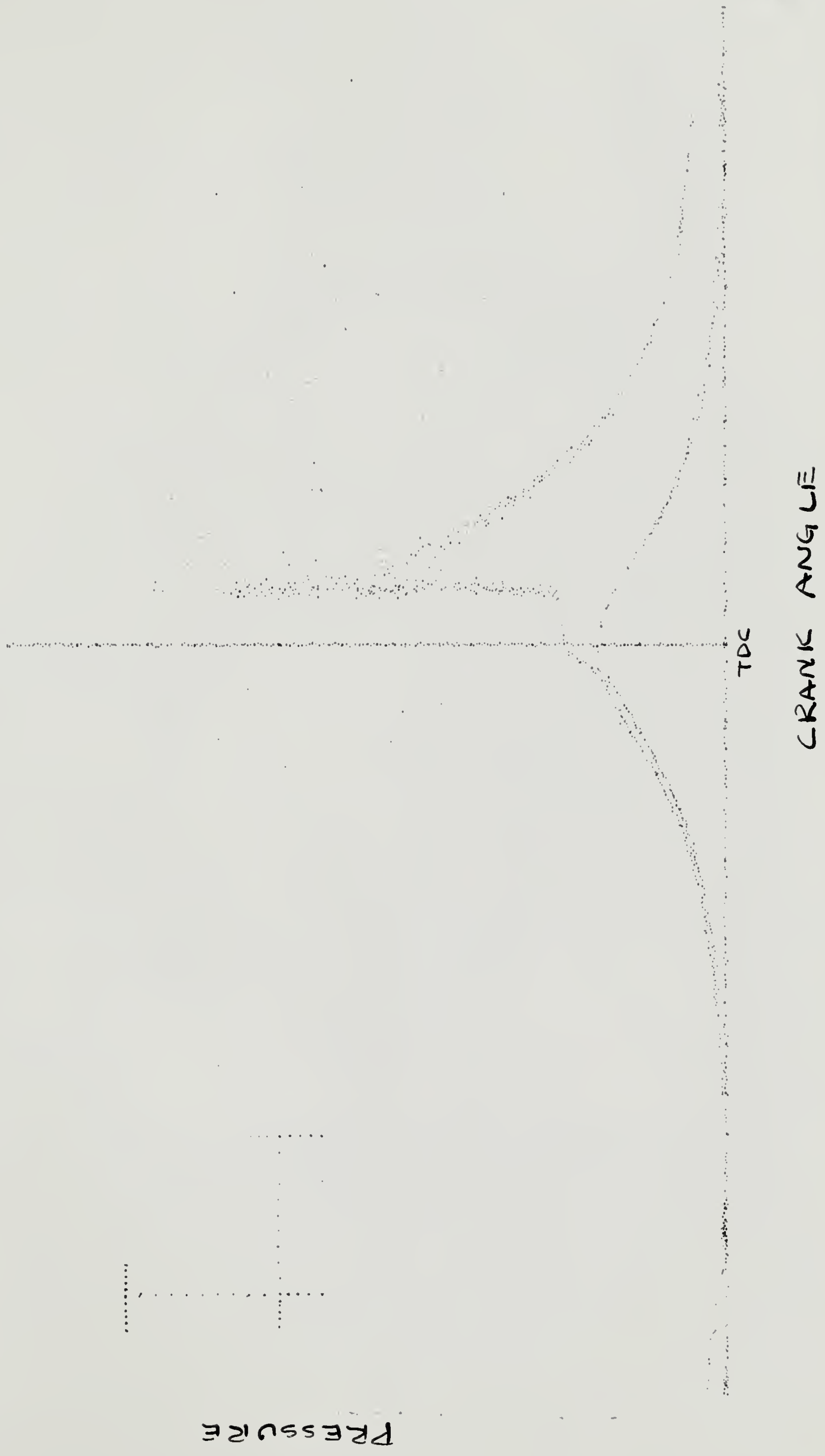
SKETCH OF PHOTOTUBE OUTPUT



A - START OF PREFLAME REACTION
B - "POINT" OF AUTOIGNITION
Z - DURATION OF PREFLAME REACTION
H - DURATION OF RADIATION

FIGURE 1

FIGURE 1A



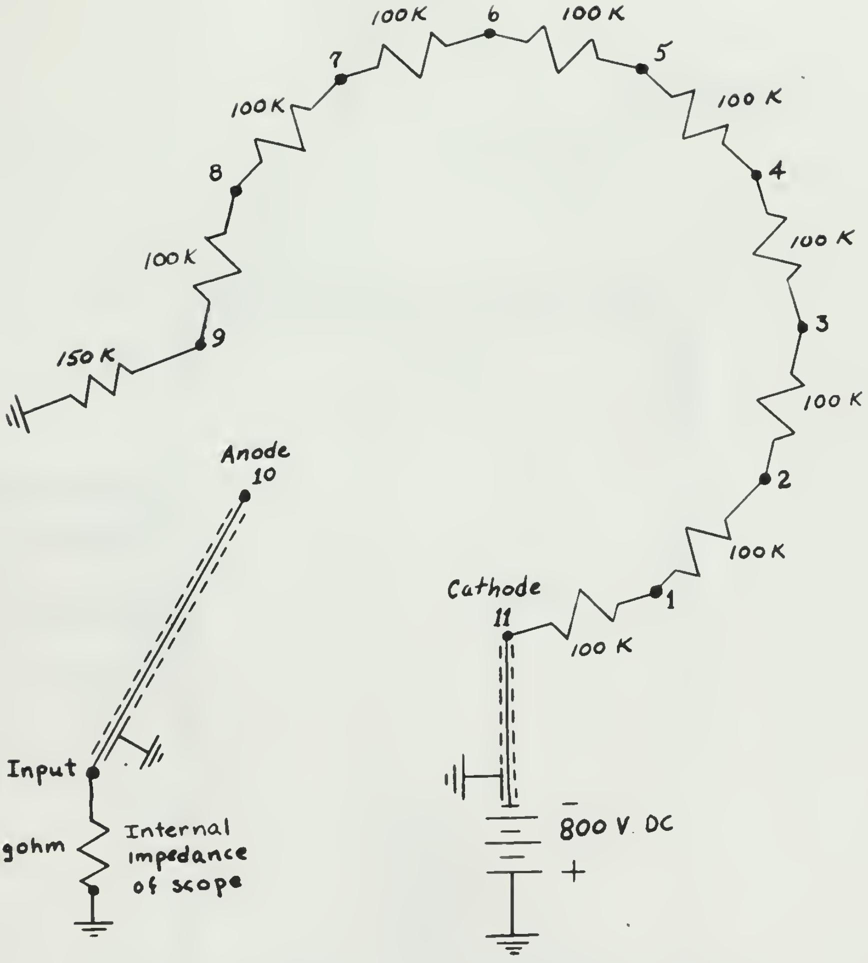


FIGURE 2. PHOTOTUBE WIRING DIAGRAM

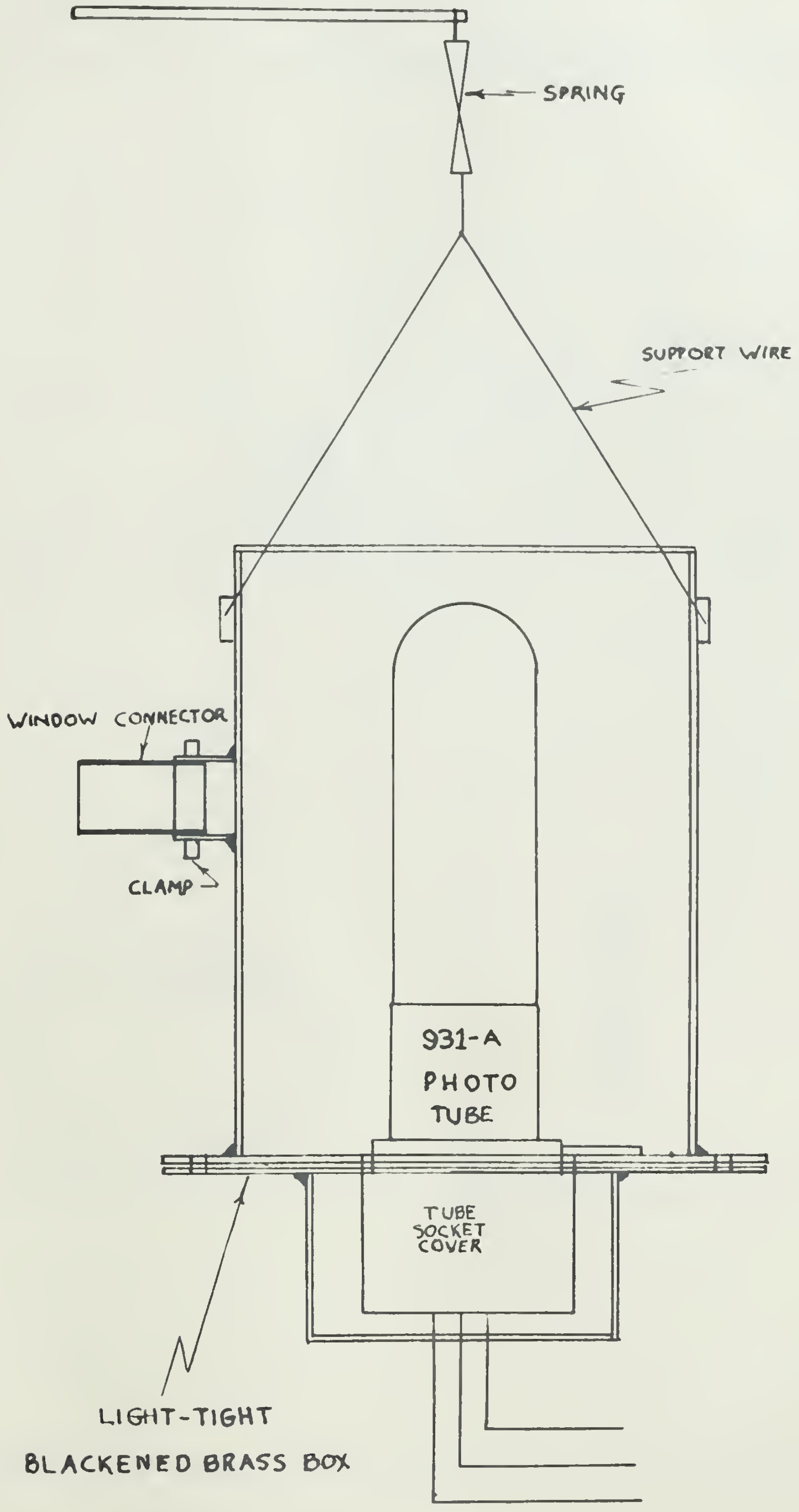


FIGURE 3 - RADIATION PHOTOTUBE PICKUP ENCLOSURE

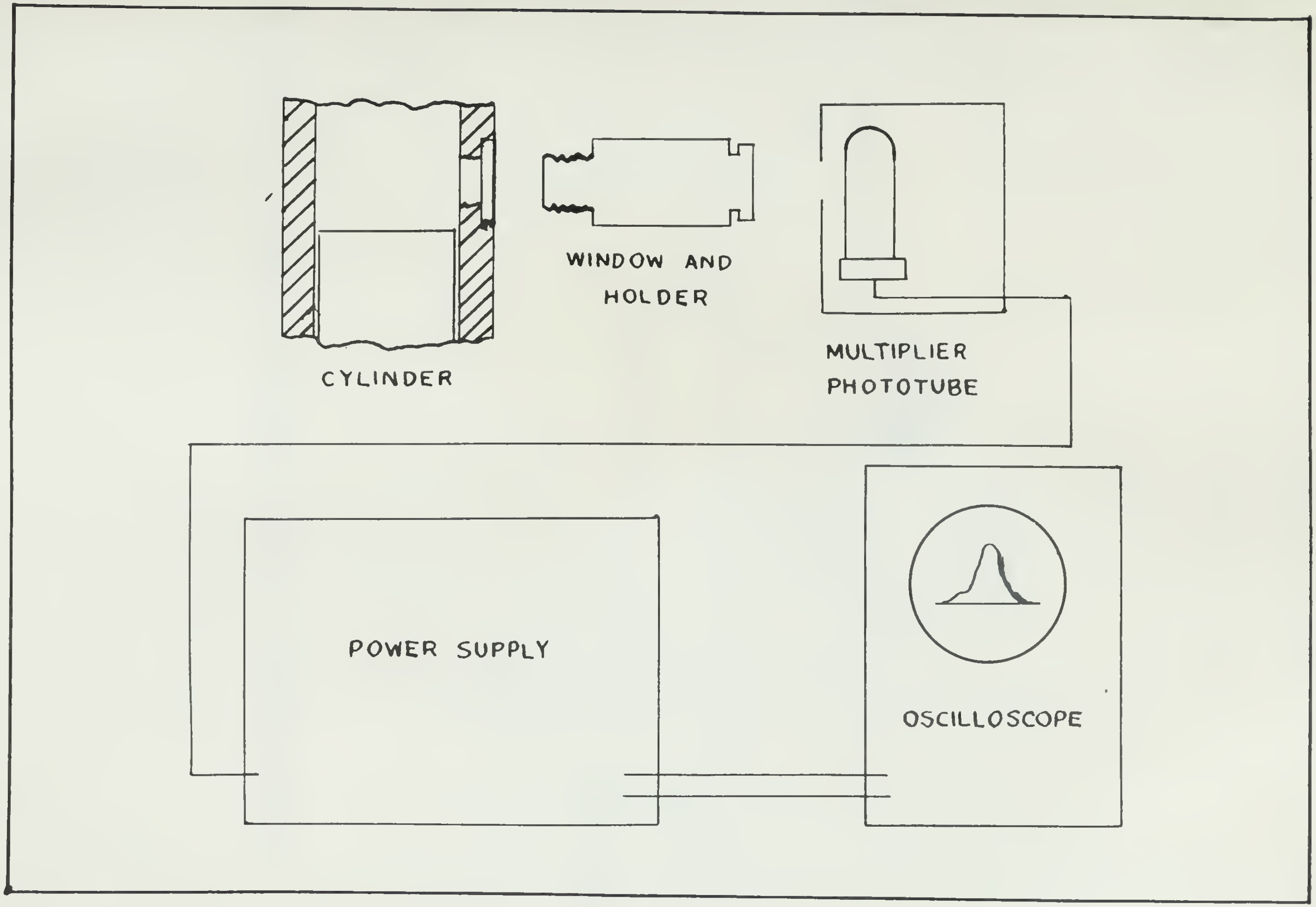


FIGURE 4 - BLOCK DIAGRAM OF RADIATION DETECTION EQUIPMENT

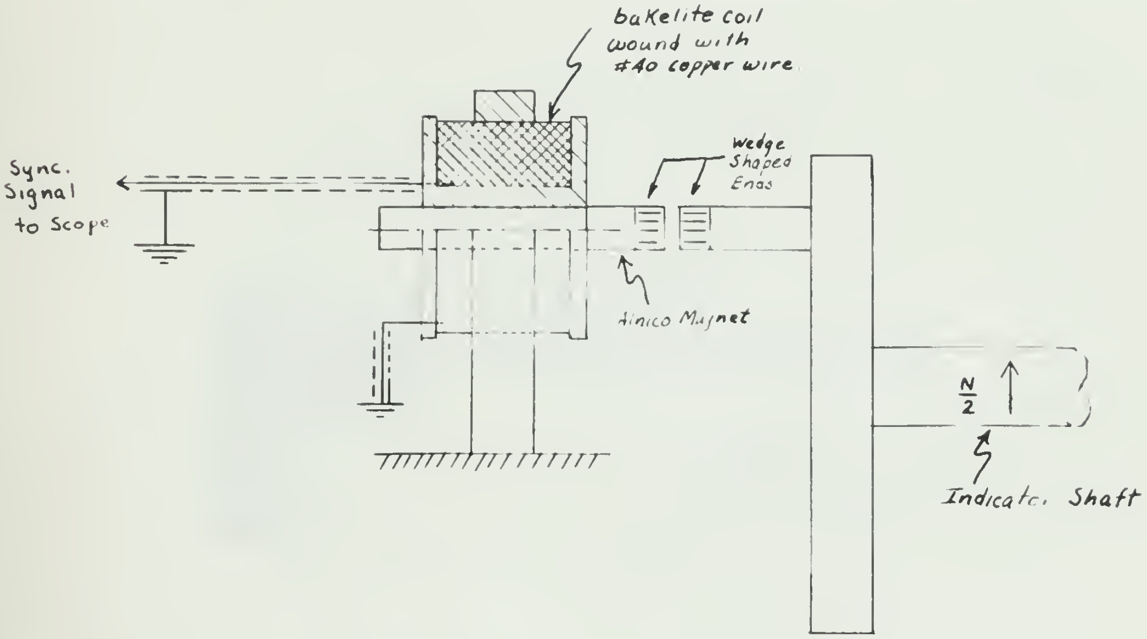


FIGURE 5. SYNCHRONIZING SIGNAL GENERATOR

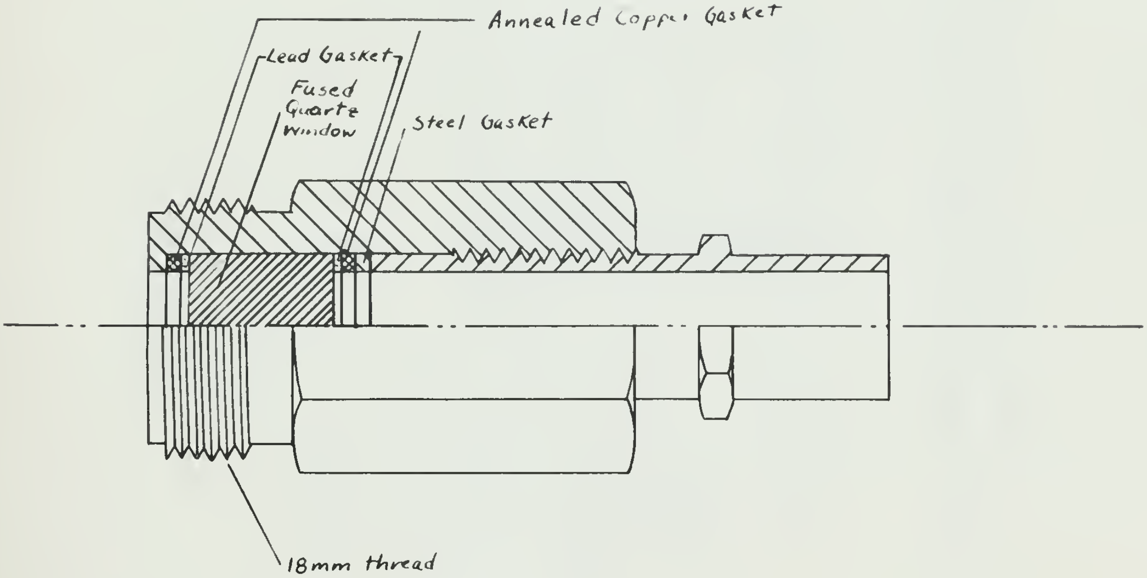


FIGURE 6

QUARTZ WINDOW AND HOLDER

Scale: 1" = ½"

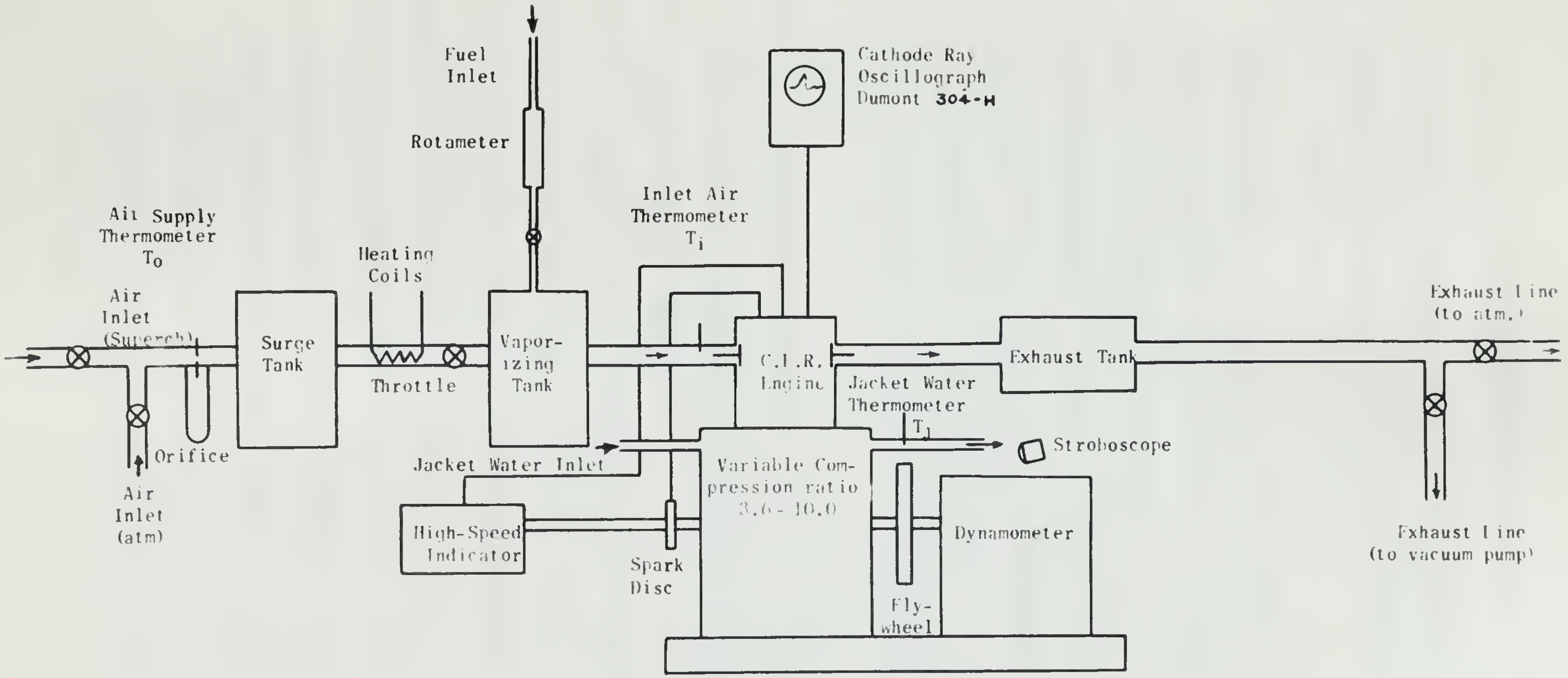


FIGURE 7 - SCHEMATIC DIAGRAM OF C.F.R. ENGINE AND AUXILIARY EQUIPMENT

(TEST FLOOR, SLOAN LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY)

III PROCEDURE

In the opinion of the authors, four basic quantities are the governing factors affecting the detonation phenomena. These are:

1. The pressure of the fuel-air charge in the cylinder which is mainly a function of the compression ratio and the inlet pressure.
2. The temperature of the fuel-air charge in the cylinder. This variable is affected by (a) the inlet temperature of the charge, (b) the compression ratio, and (c) the cylinder wall temperature.
3. Time effects, which are basically dependent upon the rate of compression and are therefore a function of the engine speed.
4. The chemical composition of the fuel-air charge.

By considering the above factors it can be seen that in order to make any logical investigation the large number of possible variables must be reduced. For our investigation the following variables have been regulated under various operating conditions in order to keep them constant.

1. Temperature of the fuel-air charge at the inlet to the engine cylinder, T_i.
2. Temperature of the cooling water leaving the cylinder jacket, T_W.

3. Temperature of the lubricating oil, T_{oil}.
4. Inlet pressure of the charge to the cylinder, P_i.
5. Type of fuel; normal heptane reference fuel (0 octane) was used throughout.
6. Fuel-air ratio, F; set at 0.08, which is approximately the best power ratio.
7. Pressure in the exhaust manifold, P_e; atmospheric.

By keeping the above factors constant the pressure, temperature, and time effects should, in the main, be functions of two variables, the compression ratio and the engine speed. Under actual engine operation this assumption agrees with internal combustion engine theory and experimental tests. The actual test procedure was based on these considerations and carried out in the following sequence. For each set of runs the brake reading, start of the preflame reaction, the point of autoignition, and the duration of the preflame reaction were recorded. This information was obtained by moving the spark signal along the phototube output trace on the cathode ray oscilloscope as explained in the Introduction.

A. The first set of runs, numbers 1 to 7, were made at a constant speed of 1100 rpm. The compression ratio was varied from 5.5 to 8.5. The other engine operating conditions, which were held constant, were oil temperature, 140F; inlet air temperature, 170F; cylinder jacket cooling

water temperature, 180F; and fuel-air ratio, 0.08.

B. The next set of runs, numbers 8 to 11, were made at a constant compression ratio of 8.5. The speed of the engine was varied from 1000 to 1400 rpm.

C. In order to study the effect of compression ratio and engine speed in more detail, the succeeding set of runs (numbers 12 to 37) were made at the compression ratios of 6.0, 6.6, 7.0, and 7.5. For each compression ratio a complete set of data, as discussed above, was taken over a speed range of 900 to 1500 rpm.

D. The next set of runs, numbers 38 to 49, were made using a constant value of pounds of air per suction stroke, Ma/N. This was accomplished by throttling the air flow to the engine. A compression ratio of 6 was used in order to compare the results with those of A. This set was conducted in two sections. Runs 38 to 43 were taken with the inlet fuel-air charge temperature at 170F, the same as the preceding runs. Runs 44 to 49 were carried out in exactly the same manner except that an inlet temperature of 184F was used to investigate the effect of the inlet temperature on the autoignition of the fuel-air charge. The purpose of this set of runs was to investigate the combustion efficiency alone, since under these conditions the variation of air consumption does not influence the process.

E. To investigate the flexibility of the total detonation cycle using this fuel, a set of runs (numbers 50 to 54) was made at a compression ratio of 6 and 1000 rpm for various inlet pressures. This compression ratio was chosen since it seemed most promising in the light of a practical engine as brought out by the foregoing runs.

To obtain the indicated mean effective pressure of the various runs, the brake mean effective pressure as obtained from the dynamometer readings during detonation was added to the friction mean effective pressure as obtained from the dynamometer readings while motoring the engine.

During representative runs strip photographs were made of the phototube output trace on the cathode ray oscilloscope. These are shown in Figures 23 to 28 inclusive.

IV RESULTS

EFFECT OF COMPRESSION RATIO

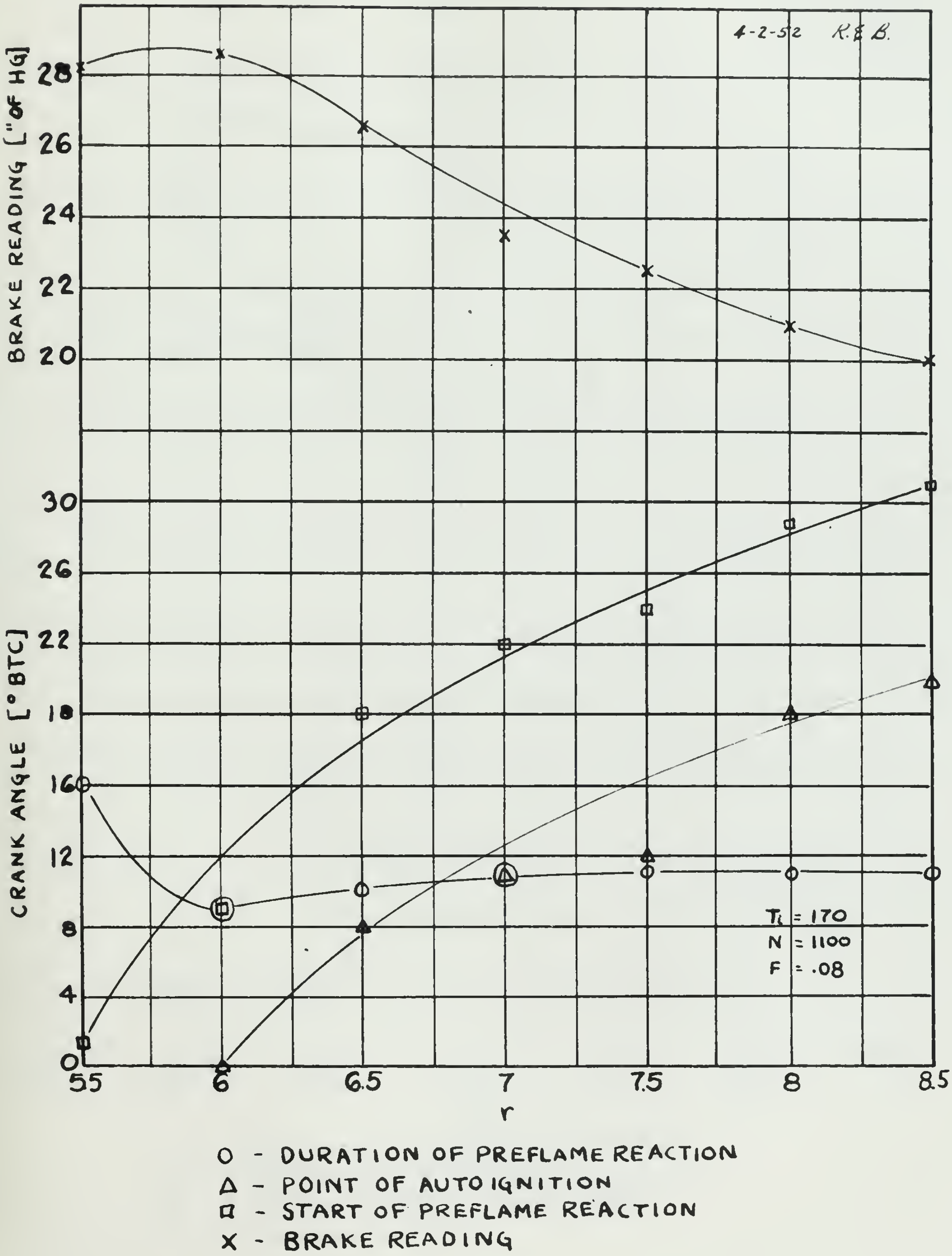
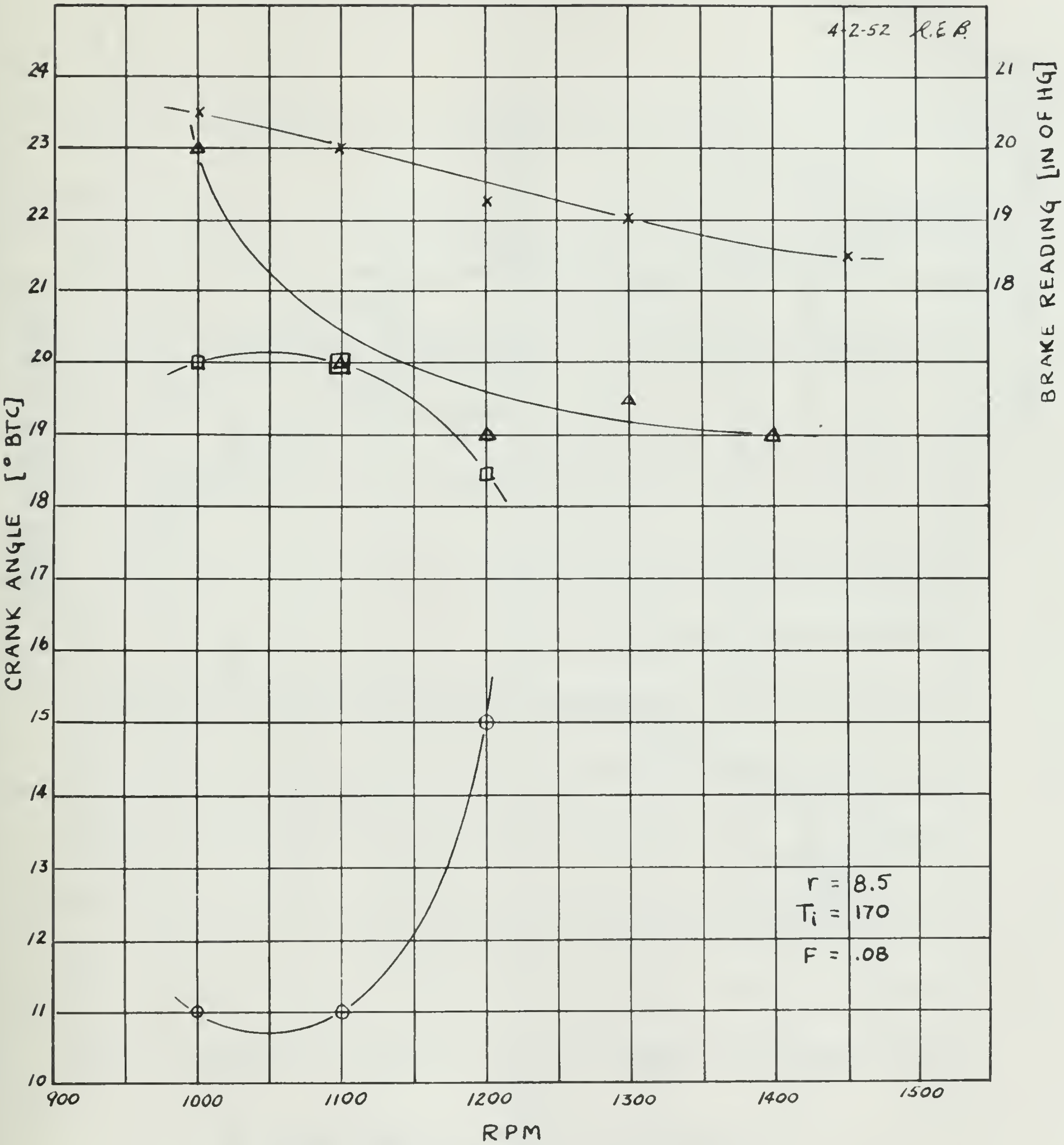


FIGURE 8

EFFECT OF RPM



○ - DURATION OF PREFLAME REACTION
Δ - POINT OF AUTOIGNITION
□ - START OF PREFLAME REACTION
X - BRAKE READING

FIGURE 9

EFFECT OF RPM

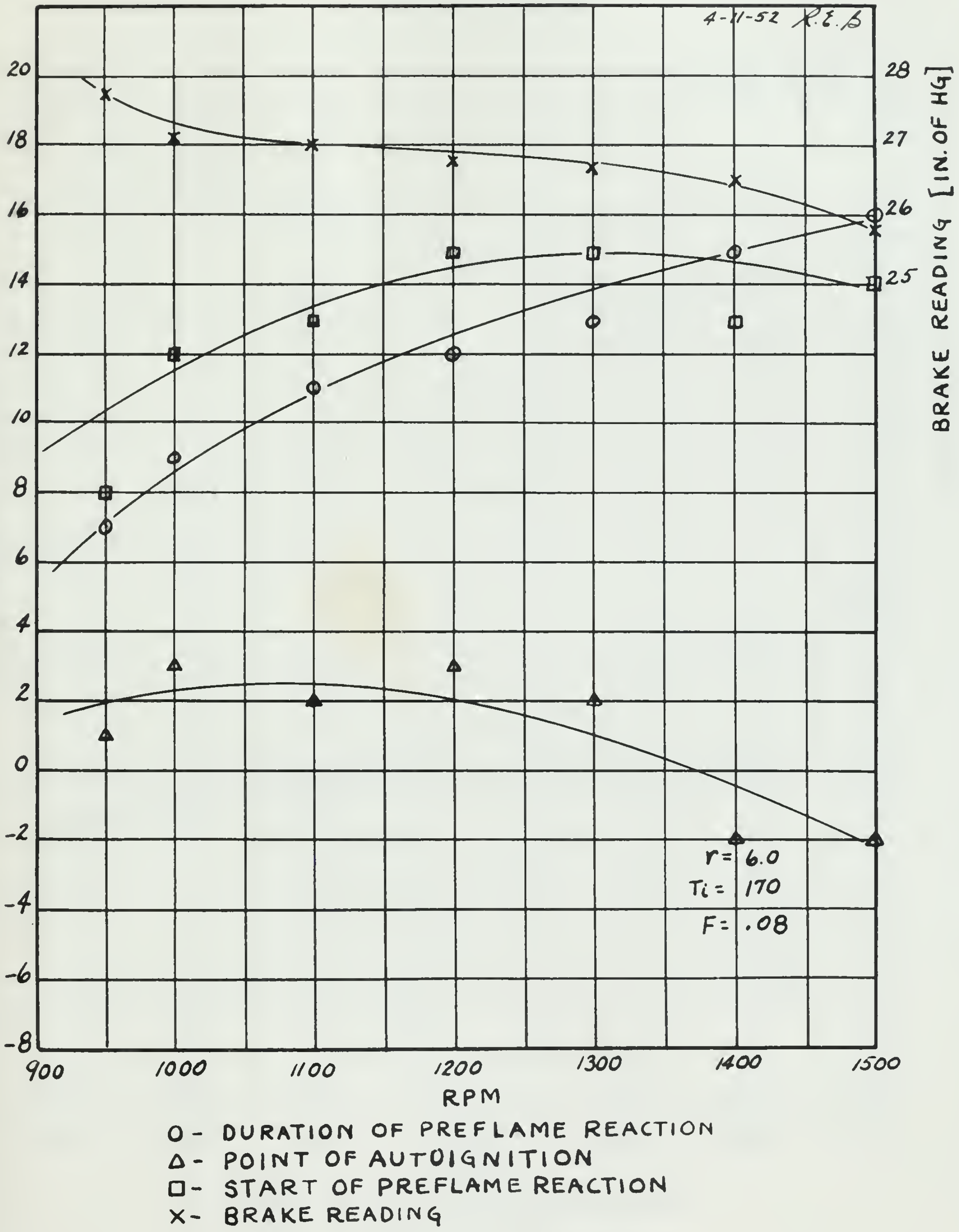


FIGURE 10

EFFECT OF RPM

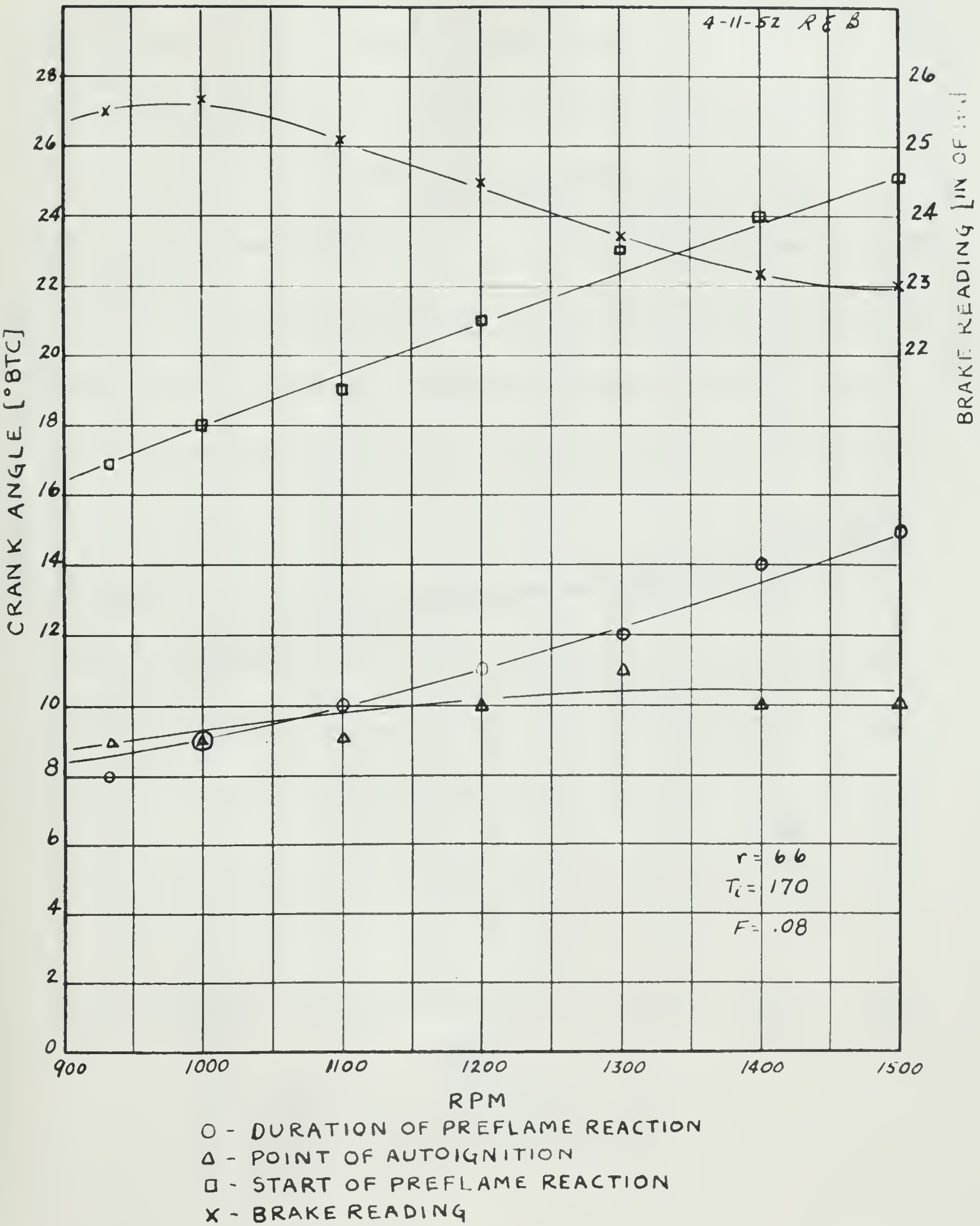
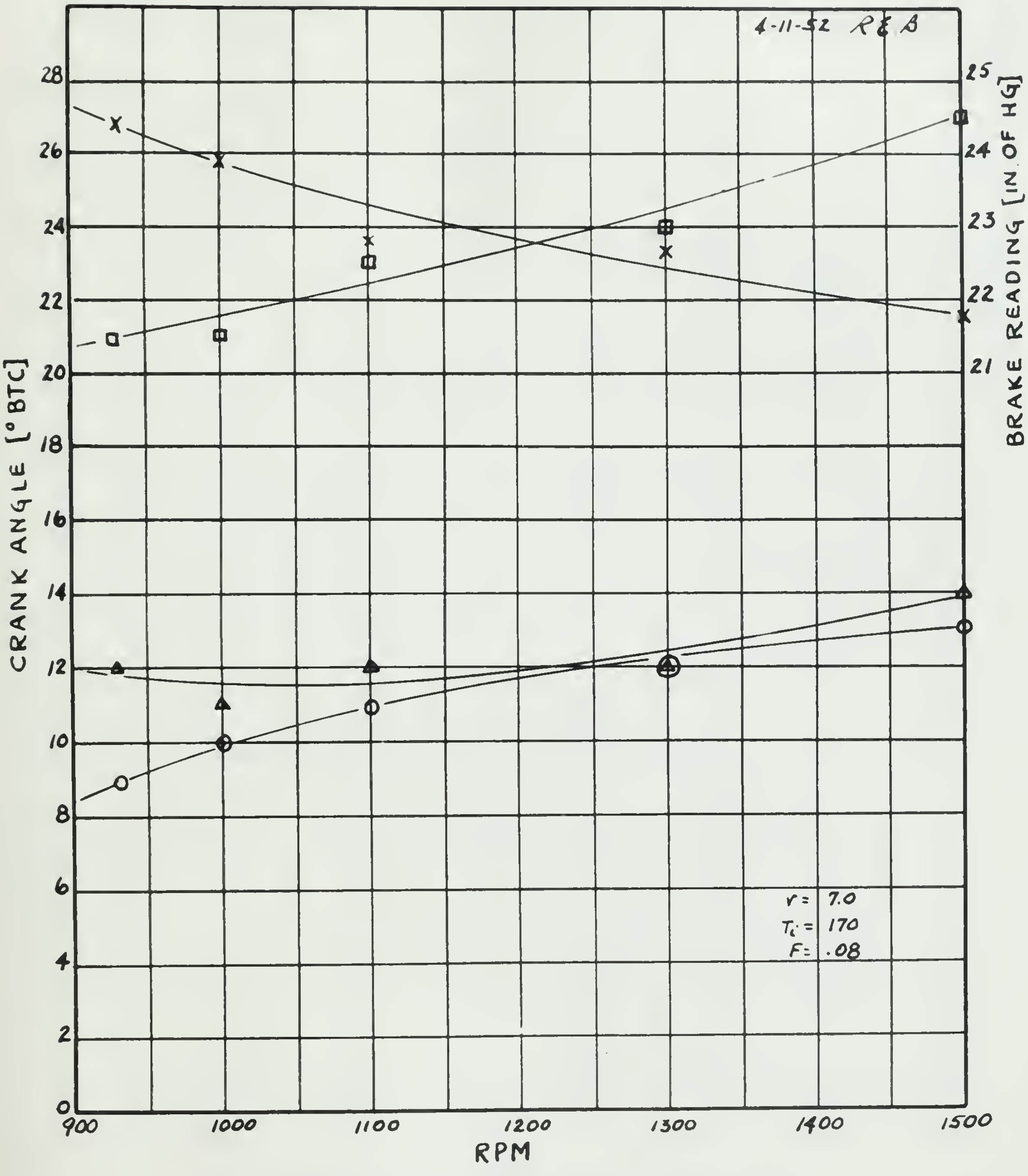


FIGURE 11

EFFECT OF RPM



O - DURATION OF PREFLAME REACTION
Δ - POINT OF AUTOIGNITION
□ - START OF PREFLAME REACTION
X - BRAKE READING

FIGURE 12

EFFECT OF RPM

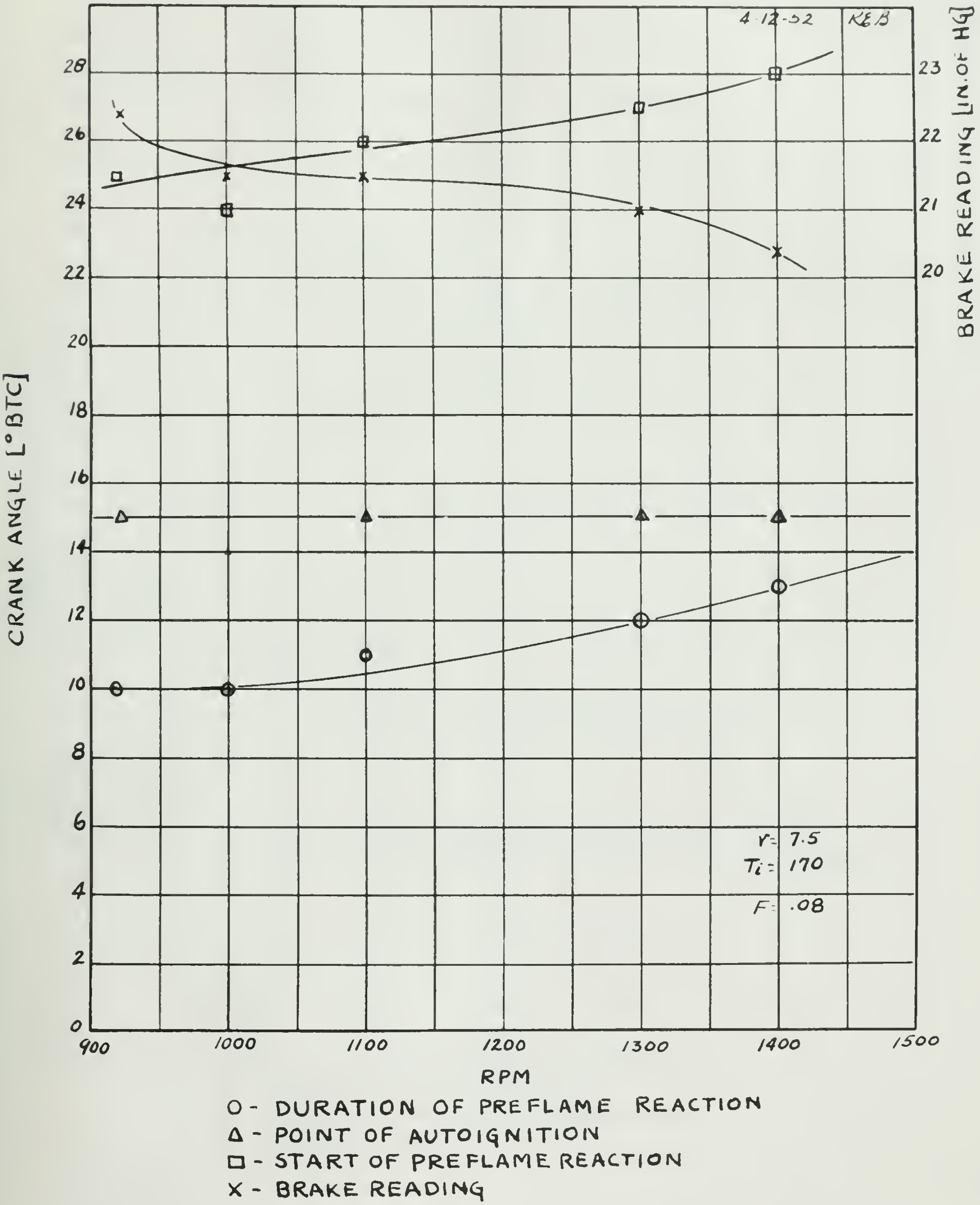


FIGURE 13

EFFECT OF RPM AT CONSTANT M_A/N

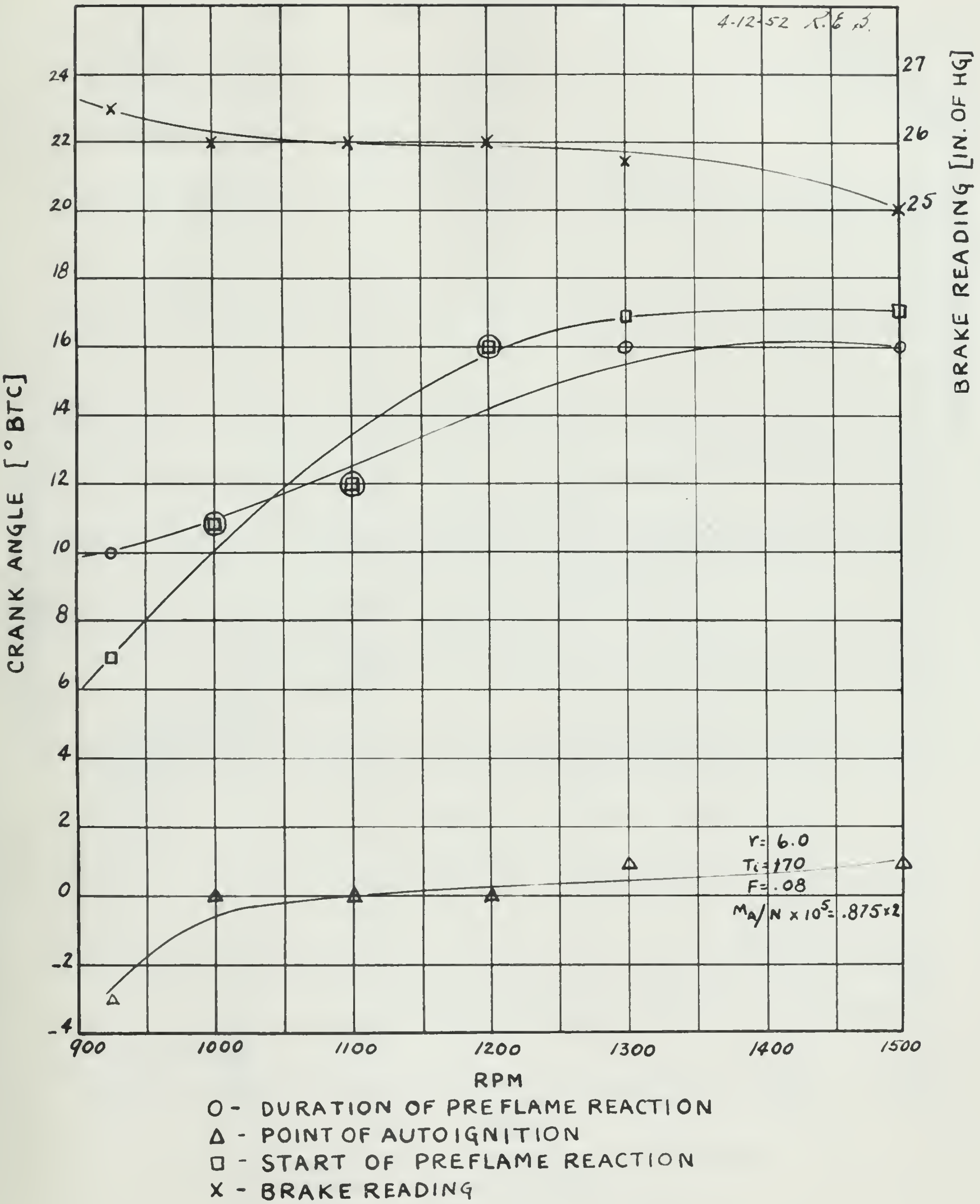


FIGURE 14

EFFECT OF RPM AT CONSTANT M_A/N

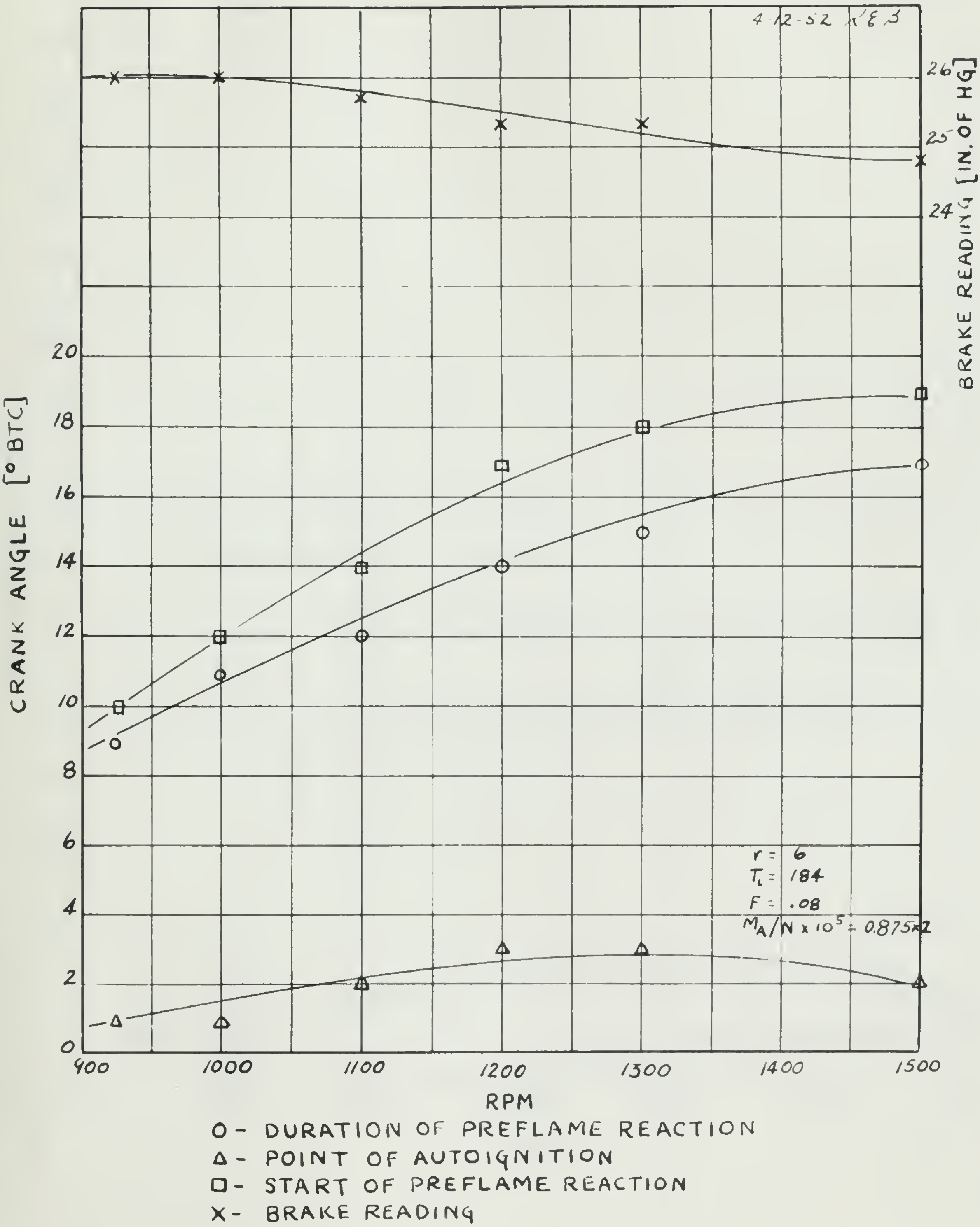


FIGURE 15

POINT OF AUTOIGNITION

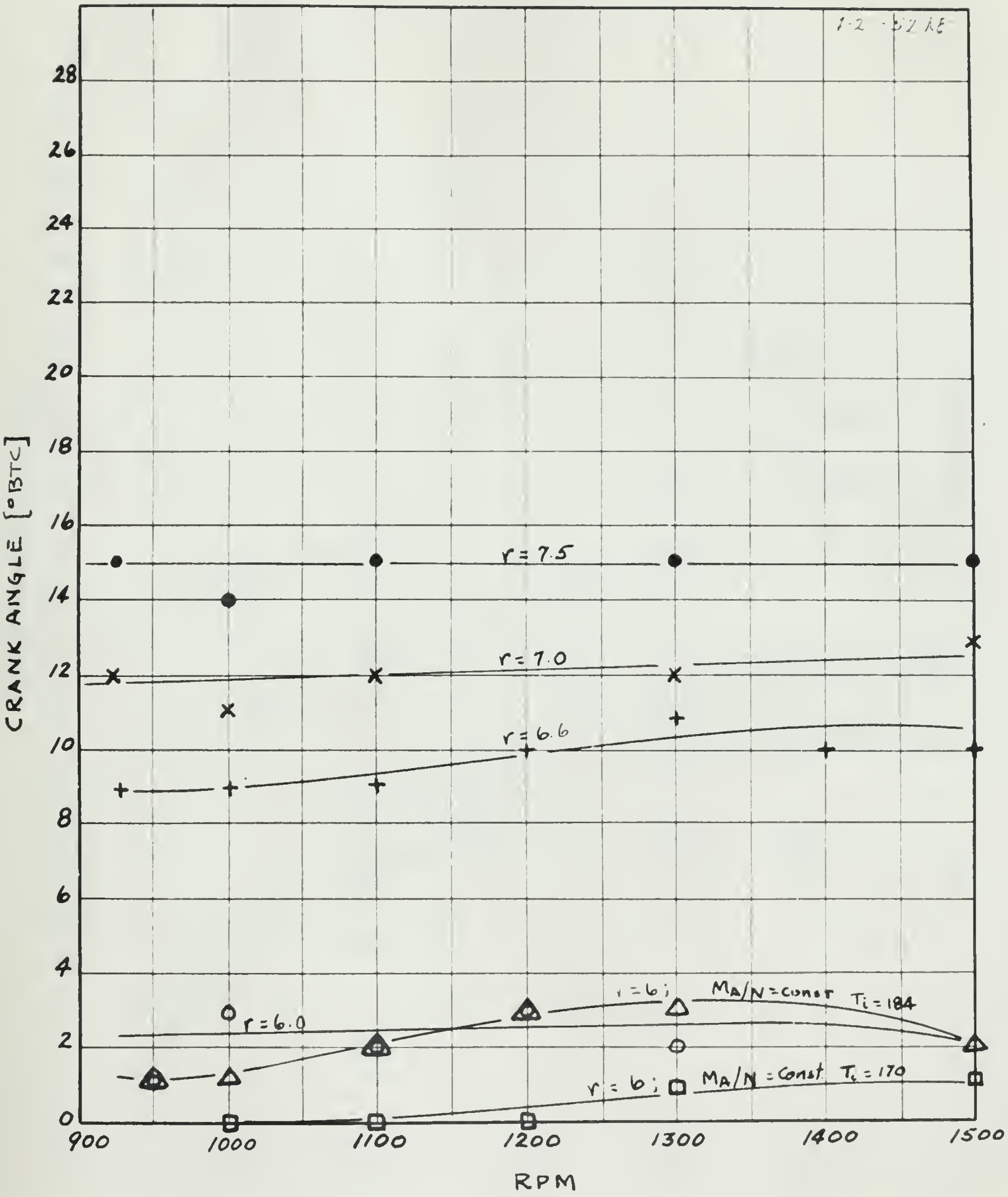


FIGURE 16

START OF PREFLAME REACTION

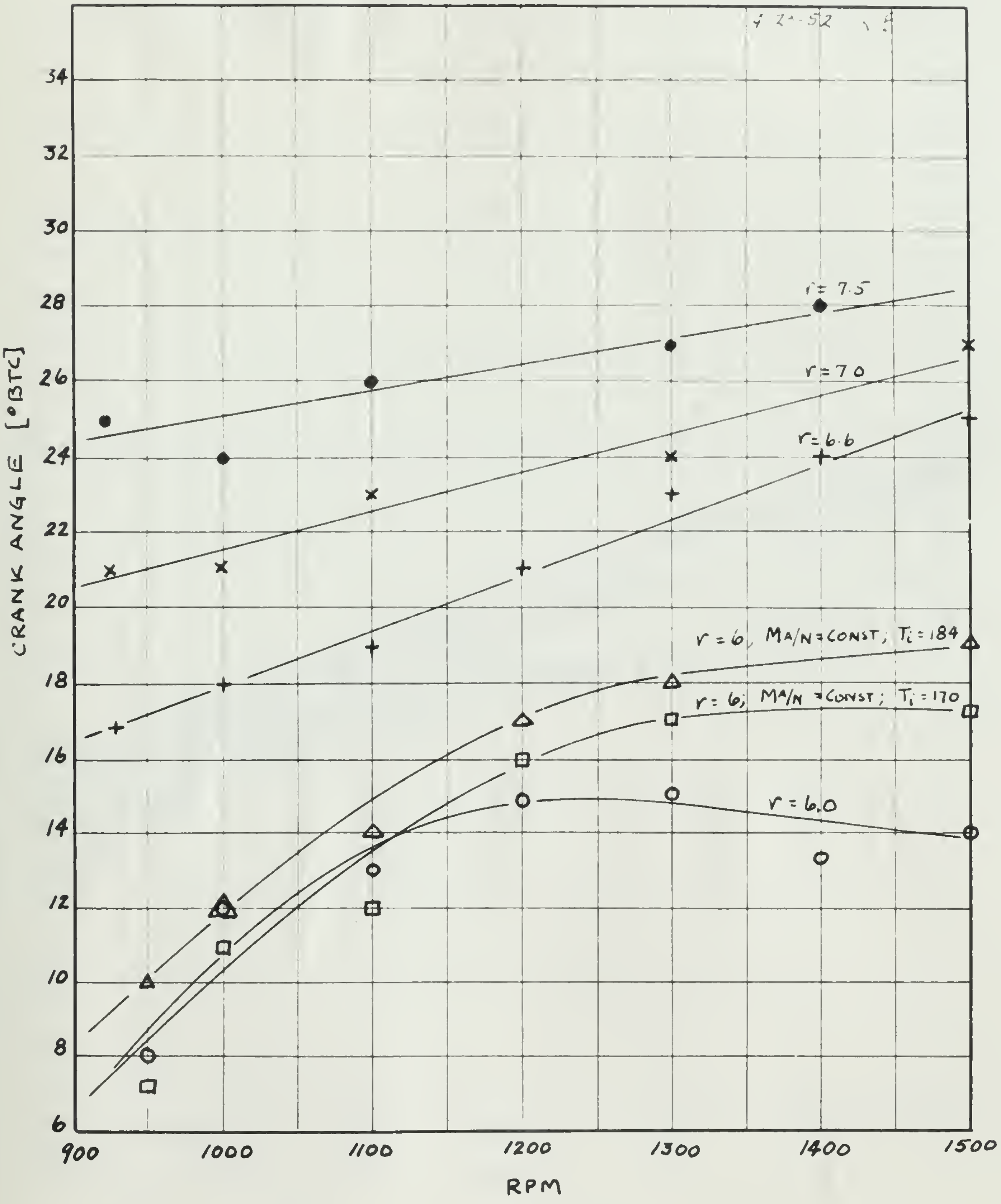


FIGURE 17

DURATION OF PREFLAME REACTION

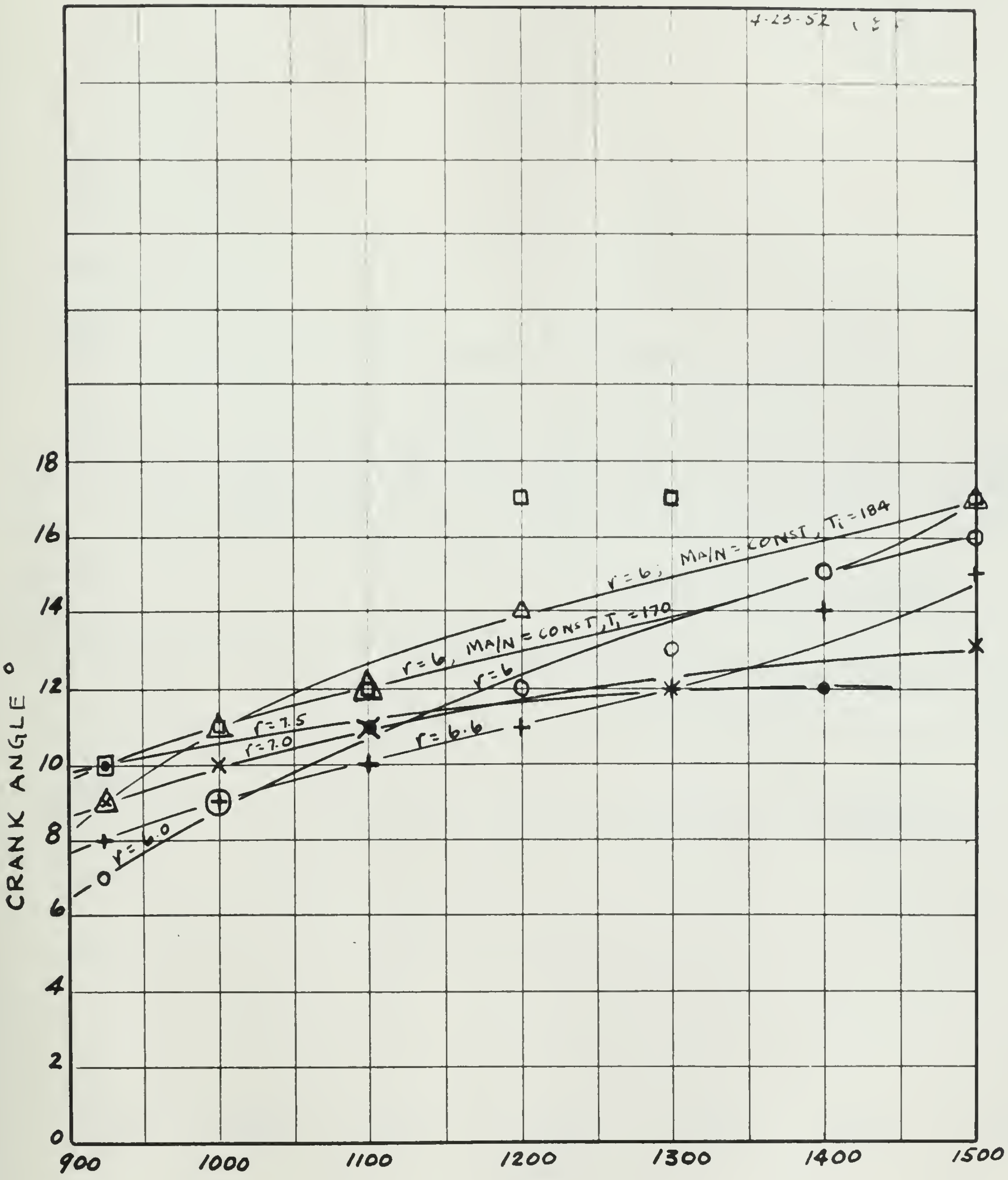


FIGURE 18

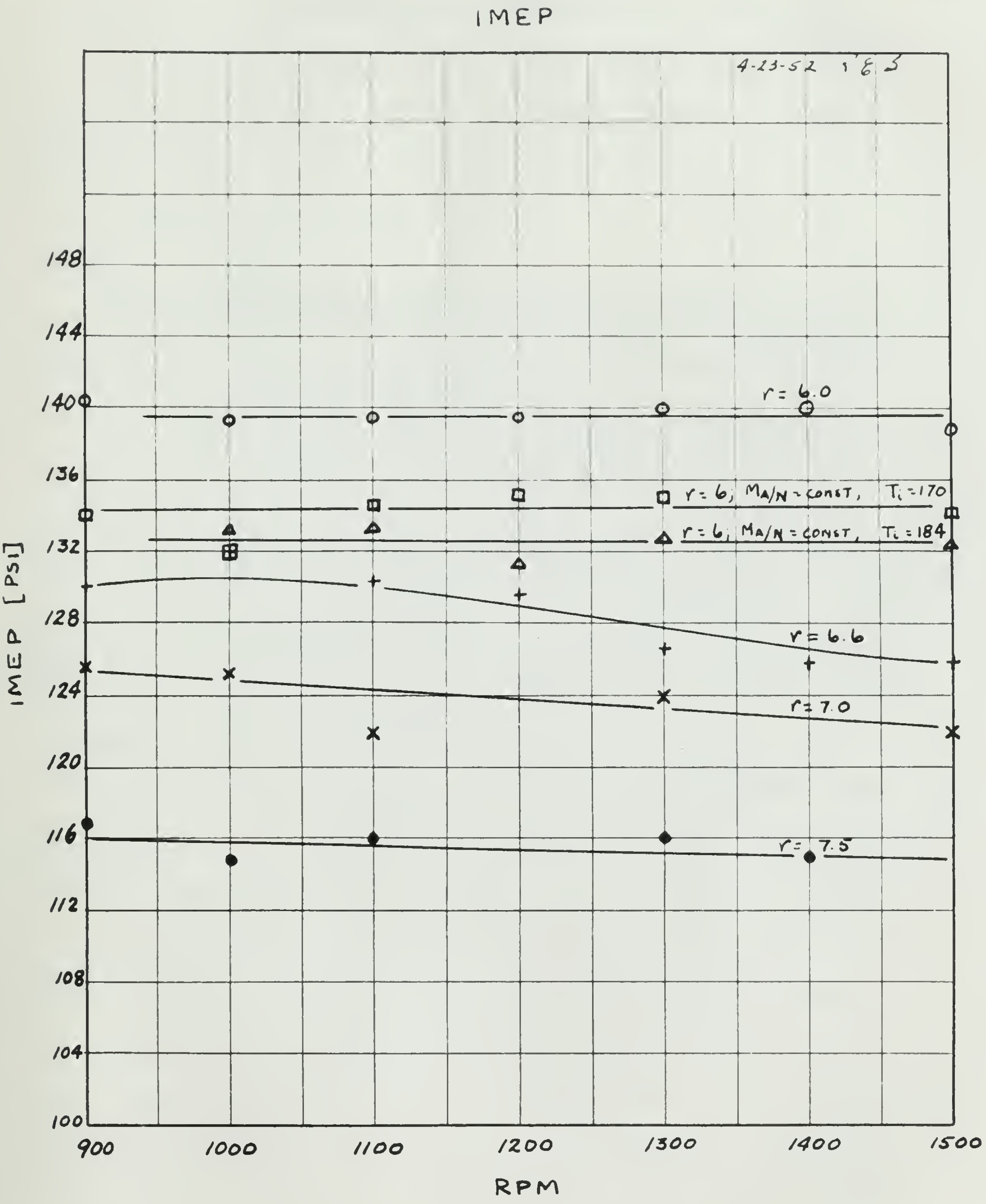

IMEP
4-23-52 1'6.5
148
144
140
136
132
128
124
120
116
112
108
104
100
IMEP [PSI]
900
1000
1100
1200
1300
1400
1500
RPM
r = 6.0
r = 6; MA/N = CONST, Ti = 170
r = 6; MA/N = CONST, Ti = 184
r = 6.6
r = 7.0
r = 7.5

FIGURE 19

V DISCUSSION OF RESULTS

The basic equation or definition of the indicated mean effective pressure of an internal combustion engine is

$$IMEP = \rho_i \, e \, F \, E_c \, \eta_i \, 778/144 \qquad (1)$$

where

$IMEP = \frac{\text{work/cycle}}{\text{cylinder displacement volume}}$; (psi)

ρ_i = density of the charge at the inlet to the cylinder; (lb/ft^3)

e = volumetric efficiency = $\frac{\rho \text{ in the cylinder}}{\rho \text{ inlet to cylinder}}$

$= \frac{\rho_1}{\rho_i}$

F = fuel-air ratio; (lbs fuel/lb. of air)

E_c = heating value of the fuel; (BTU/pound) generally taken at 19,000

η_i = indicated cycle efficiency

778/144 = units conversion factor

The following discussion is based on this basic definition and an attempt is made to correlate the test results with the definition. In all runs, except the two in which the value of Ma/n (pounds of air/cycle) was held constant, the air flow was allowed to vary with the engine speeds. The fuel flow was varied in order to keep the fuel-air ratio constant at all times. In this manner the product $F \, E_c \, 778/144$ was held constant. From Equation (1) it can be seen that any variation in the indicated mean effective

pressure would then be due to a variation in the product $\rho_i e \eta_i$. Assuming that the fuel-air charge at the cylinder inlet is a perfect gas, the perfect gas law may be used to determine the inlet density,

$$\rho_i = \frac{P_i}{R\ T_i} \tag{2}$$

where

P_i = Pressure at the cylinder inlet; (lbs/ft^2)

R = Gas constant for air; (53.39 ft-lb/lb Fabs)

T_i = Inlet temperature to the cylinder; (Fabs)

The inlet pressure and temperature were recorded for all tests so that the inlet density was readily computed.

Internal combustion engine theory defines the volumetric efficiency, e, as the density of the charge in the cylinder divided by the density of the charge at the cylinder inlet. In equation form it is expressed

$$e = \frac{Ma}{n\ Vd\ \rho_i} \tag{3}$$

where

Ma = Mass rate of flow of air to the cylinder in pounds per second

n = Number of suction strokes per second

Vd = cylinder displacement volume in cubic feet

Orifice readings gave the value of Ma, Vd is fixed by the cylinder dimensions, and n is merely the revolutions per second of the engine divided by 2 for the 4-stroke engine used. A plot of the volumetric efficiency against speed is given in Figure 20. A shrouded inlet valve was used for all

runs. From these considerations and Equation (1) it was possible to determine the indicated cycle efficiency of the total detonation cycle under various engine operating conditions. Rearrangement of Equation (1) shows this mathematically as

$$\eta_i = \frac{\text{IMEP}}{\rho_i \ c \ F \ E_c \ 778/144} \qquad (4)$$

Figure 21 is a plot of the indicated cycle efficiency for various operating conditions.

By definition the friction mean effective pressure is equal to the indicated mean effective pressure minus the brake mean effective pressure. As discussed in chapter XI of Reference (1) the practice of using the brake reading of the motored engine to obtain the friction mean effective pressure gives results which are of the order of ± 5% accurate. This has an overall effect on the value of the indicated mean effective pressure of about ±1½%. In the absence of pressure indicator cards this is our best estimate of the engine friction under running conditions. Internal combustion engine theory and practice assume that the motoring friction readings are a fair indication of the magnitudes involved. It is felt, therefore, that the values of indicated mean effective pressure thus derived are accurate to within ±1.5%.

The indicated efficiency is a direct measure of the efficiency of the combustion process in the cylinder.

The following discussion is designed to correlate the indicated cycle efficiency(Figure 21) with the data on the preflame reaction and autoignition phenomena shown in the results in Figures 16 through 18. Figures 16 through 18 are cross plots of Figures 8 through 15, presenting an integrated picture of results of various test runs. Interpretation of the test results are made in two sections. Section 1 treats the results from a combustion viewpoint and section 2 discusses the possibilities of using the total detonation cycle as a practical engine cycle.

Section 1a. Engine operation under full throttle conditions.

Figure 17 shows that increasing the speed and increasing the compression ratio cause the preflame reaction to occur earlier in the cycle. From Figure 18 it can be seen that as the compression ratio is increased the duration of the preflame reaction, in crank angle degrees, tends to decrease for a given speed. However, for a given compression ratio, the duration of preflame reaction in crank angle degrees increases with increasing speed. The effect of the variation in the start of the preflame reaction and its duration upon the point of autoignition is shown in Figure 16. It is interesting to note that the point of autoignition in the cycle for a given compression ratio is practically constant in view of the variations in the start of the preflame reaction and its duration mentioned above.

Figure 16 indicates that the engine speed, start of preflame reaction, and its duration do not measurably affect the point of autoignition. However, the compression ratio has a noticeable effect, causing the point of autoignition to occur earlier in the cycle as the compression ratio is increased. The results of the variation in the point of autoignition on the indicated mean effective pressure and the indicated cycle efficiency are shown in Figures 19 and 21. As the point of autoignition happens earlier in the cycle, i.e., when the piston is farther from the top dead center position, the indicated mean effective pressure decreases. For a given compression ratio, however, the indicated mean effective pressure is virtually constant. This can be expected since the point of autoignition is constant under this condition.

Equation (4) states that the indicated efficiency is proportional to the ratio of the indicated mean effective pressure to the product of the inlet density and the volumetric efficiency. It has been shown that the indicated mean effective pressure is constant for a given compression ratio over the speed range investigated. The inlet density, as computed from Equation (2), varied by only one tenth of one percent over the speed range and therefore can be considered constant. Variation in volumetric efficiency is shown in Figure 20. Since the inlet density was constant,

the variation in the cylinder density, ρ_1, would be of the same form as the volumetric efficiency curve. The resultant indicated efficiency curves are shown in Figure 21. It may be noted that the efficiency curves have the inverse curvature of the volumetric efficiency curves, the minimum indicated efficiency occurring at 1100 rpm, the speed at which the volumetric efficiency is a maximum.

The highest indicated efficiency and indicated mean effective pressure are obtained at the lowest compression ratio investigated. Figure 16 shows that under this condition the point of autoignition was experienced closest to top dead center. This is in agreement with the theory stated in the Introduction. For these conditions it may be concluded that the indicated cycle efficiency of the total detonation cycle is mainly a function of the compression ratio. Slight variations of the indicated cycle efficiency over the speed range may be due to heat transfer effects.

Section 1b. Engine operation keeping Ma/n constant.

For the runs in which the value of Ma/n was held constant, the general trends of the start of preflame reaction, its duration, and the point of autoignition were the same as for the full throttle conditions. From Figure 19 it can be seen that the indicated mean effective pressure was constant but lower than the indicated mean effective pressure for the full throttle run at the corresponding compression ratio and inlet temperature. This was the variation in the cylinder density, ρ_1, would be of the same form as the volumetric efficiency curve. The resultant indicated efficiency curves are shown in Figure 11. It may be noted that the efficiency curves have the inverse curvature of the volumetric efficiency curves, the minimum indicated efficiency occurring at 1800 rpm, the speed at which the volumetric efficiency is a maximum.

The highest indicated efficiency and indicated mean effective pressure are obtained at the lowest compression ratio investigated. Figure 10 shows that under this condition the point of autoignition was displaced closest to top dead center. This is in agreement with the theory stated in the introduction. For these conditions it may be concluded that the indicated cycle efficiency of the ideal autoignition cycle is mainly a function of the compression ratio. Slight variations of the indicated cycle efficiency over the speed range may be due to heat transfer effects.

Section 16. Engine operation keeping A/F constant.

For the runs in which the value of A/F was held constant, the general trends of the speed of ignition reaction, its duration, and the point of autoignition were the same as for the runs discussed previously. From Figure 12 it can be seen that the indicated mean effective pressure was reduced and lower than the indicated mean effective pressure for the full throttle run at the corresponding compression ratio and inlet temperature. This was due to the fact that the mass rate of flow of air to the cylinder was arbitrarily chosen at a lower value. The mass rate of flow of air was set about four percent lower for the throttled run, hence, the indicated mean effective pressure was also about four percent lower. Therefore it can be concluded that if the mass rate of flow to the cylinder had been the same in both runs, the indicated mean effective pressure curves would have coincided. From Equation (3) it can be seen that for Ma/n equal to a constant the cylinder density, which is equal to the product of and e, would be constant. Therefore, from Equation (1) any change in the indicated mean effective pressure would be due to a change in the indicated cycle efficiency. Figure 19 shows that the indicated mean effective pressure was constant for constant Ma/n. Therefore the indicated efficiency was constant as can be seen in Figure 21.

When the inlet temperature was raised to a higher value for this type of run, the indicated mean effective pressure decreased. This was due to the fact that the indicated cycle efficiency decreased. By keeping the density of the charge in the cylinder, ρ_1, constant it can be seen from Equation (1) that the indicated efficiency is the only variable quantity affecting the value of the indicated mean effective pressure. The indicated efficiency thus indicated is a direct measure of the efficiency of the combustion process under these conditions.

The higher temperature caused the autoignition point to occur farther before top dead center with a resultant decrease in indicated efficiency and indicated mean effective pressure.

Figure 21 also shows that the indicated efficiency of the runs in which Ma/n was held constant was higher than the runs made under open throttle conditions over most of the speed range. Time did not permit further study of the effects of temperature, but it may be concluded from these runs that the inlet temperature of the charge is an important factor affecting the indicated efficiency of this type of cycle.

Section 2. Practical engine possibilities.

The previous section has shown that the maximum indicated efficiency and indicated mean effective pressure are experienced at a low compression ratio while using a low octane fuel. The indicated mean effective pressure and indicated efficiency of the total detonation cycle are higher than those of an engine of this type operated on the conventional spark ignition cycle using current automotive fuels (Reference 7). Its ability to use a much cheaper fuel speaks in its favor (Reference 8). Manufacturing costs of such an engine would be less since it does not require an ignition system or a complicated fuel injection system.

There are some disadvantages which must also be con-

sidered. The engine operating on this cycle is very noisy. However, the noise is in the high frequency range and could no doubt be silenced. The results of Figure 22 indicate a limited flexibility for such an engine while operating at varying inlet pressures since it stopped detonating when the pressure was reduced to 6½ inches of mercury below atmospheric. This indicates that load control of the engine is probably not possible through changing the mass rate of flow of air to the engine by throttling.

At the present time there are no data available as to the ability of the various engine parts to stand up under prolonged operation on the total detonation cycle. The engine used in these studies was subjected to approximately forty hours of severe detonation with no apparent deleterious effects. The result of this type of operation on engine parts could only be determined by long-range endurance testing.

AIR FLOW AND VOLUMETRIC EFF'Y

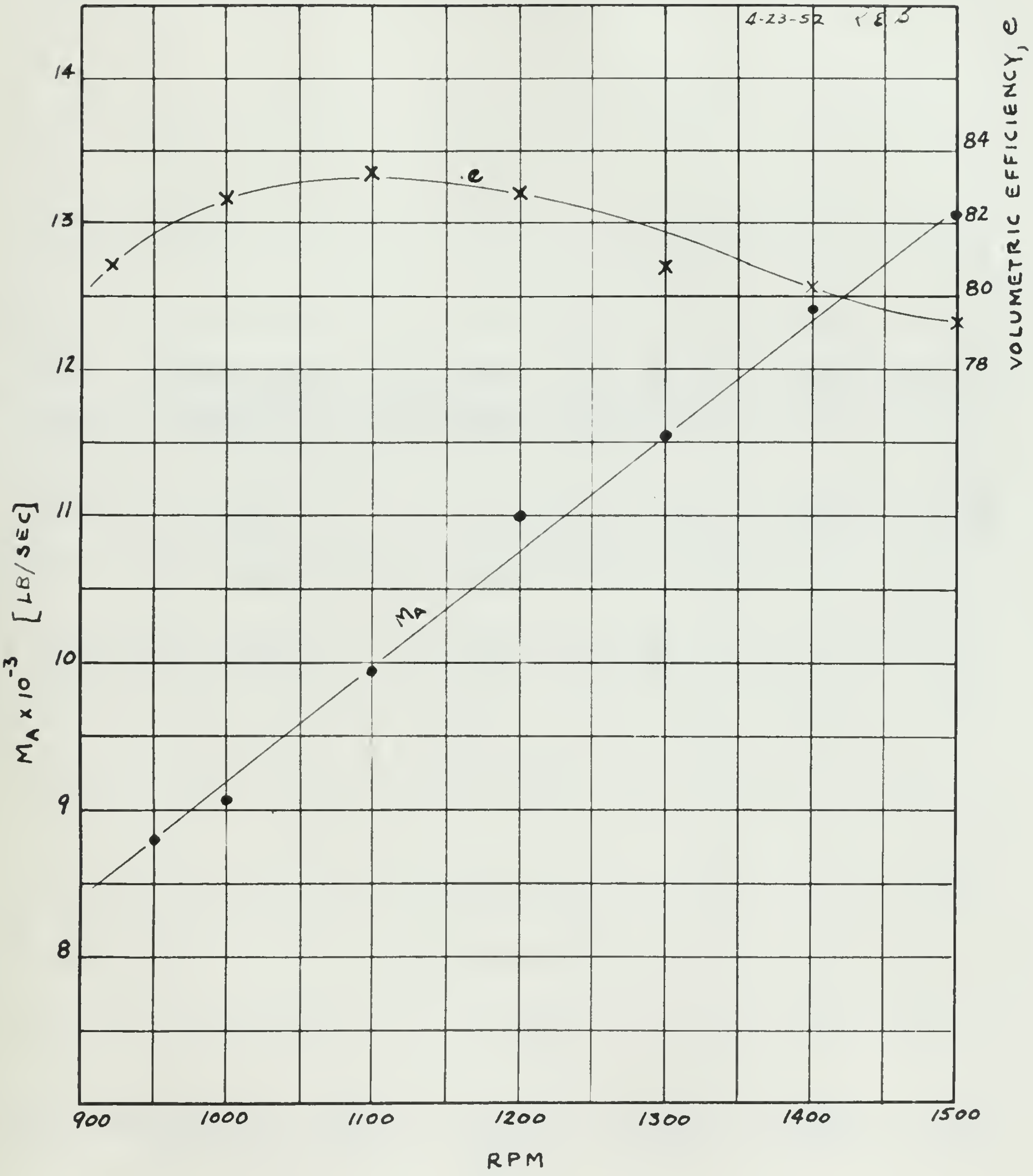


FIGURE 20

INDICATED EFFICIENCY

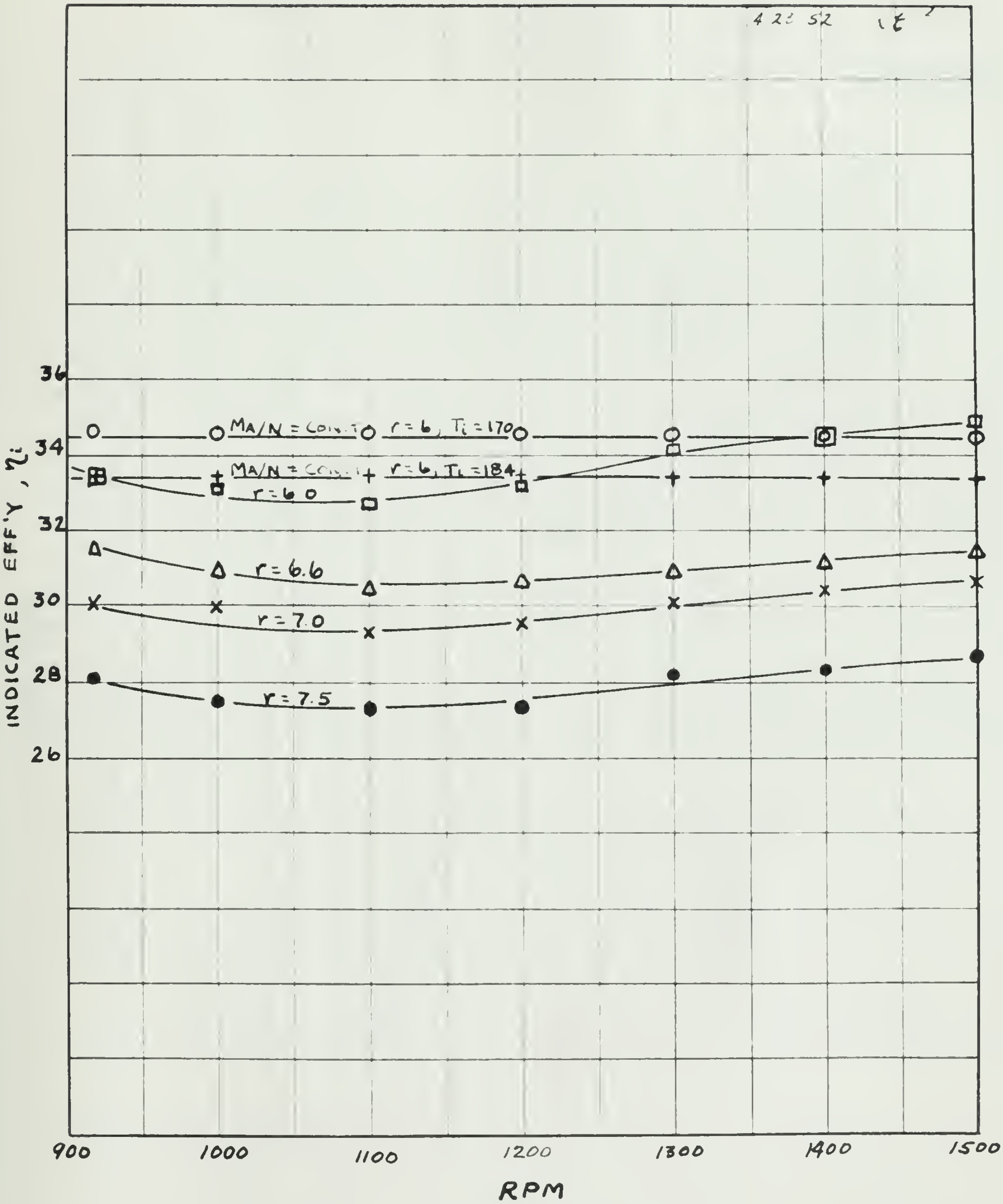


FIGURE 21

EFFECT OF INLET PRESSURE ON IMEP

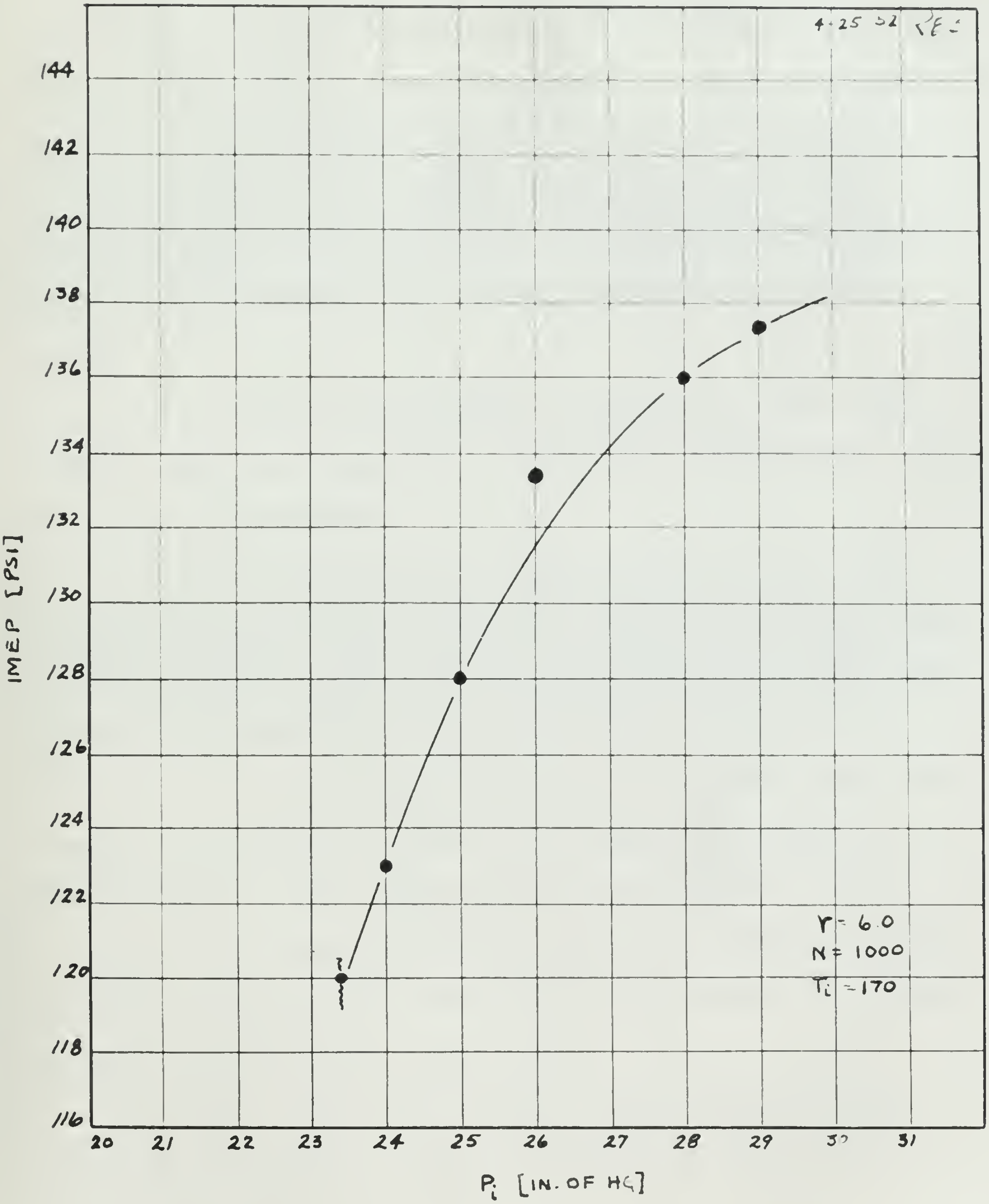


FIGURE 22

VI CONCLUSIONS

A new photoelectric technique has been applied to the study of the total detonation cycle in a single cylinder engine. This technique provides a means of determining with high precision the times at which the detonation events occur in the engine cycle. On the basis of the results thus obtained the following conclusions may be drawn:

1. It should be possible to employ the total detonation cycle as a practical engine cycle in constant speed and load applications.

2. The total detonation cycle yields higher indicated cycle efficiency and higher indicated mean effective pressure than the conventional spark ignition cycle under comparable conditions.

3. At a given compression ratio the crank angle at which the preflame reaction starts does not materially influence the crank angle at which autoignition starts.

4. At a given compression ratio the duration of the preflame reaction does not materially influence the crank angle at which autoignition starts.

5. For a given compression ratio the crank angle at which autoignition starts is virtually constant over the speed range considered.

6. For the range of compression ratios studied, 6.0 to 8.5, the highest cycle efficiency and indicated mean effective pressure were obtained at the lowest compression ratio.

7. Over the range of inlet temperatures investigated, 170 to 184F, the inlet temperature has an important effect on the indicated cycle efficiency of this type of operation.

VII RECOMMENDATIONS

In view of the results of this investigation the authors feel that this type of cycle warrants further study. Such study might be profitably be pursued along the following lines:

1. In light of producing a practical engine for operation on this cycle, further flexibility tests should be made.

a. Investigate operation of the engine using this cycle over a wide range of inlet pressure.

b. A complete study of the effect of varying the temperature of the fuel-air charge at inlet and the compression ratio should lead to the determination of a prescribed set of operating conditions which would produce autoignition at top dead center. As borne out by the authors' work this is a condition to strive for in using this cycle.

2. Investigate the use of various other cheap fuels which might be employed in this cycle.

3. A development study should be made determining the effect of prolonged operation on the total detonation cycle upon the various engine parts. Critical parts include the piston, piston rings, crankshaft, bearings and valves.

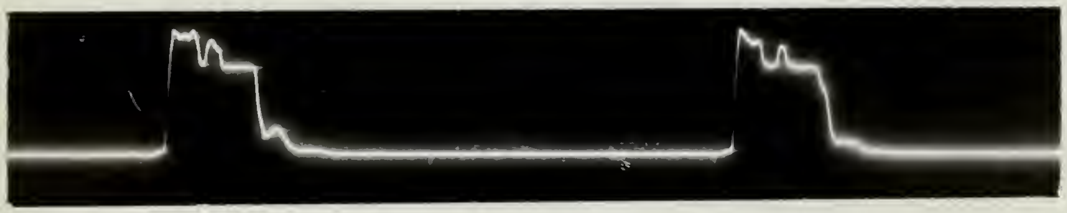


Figure 23a

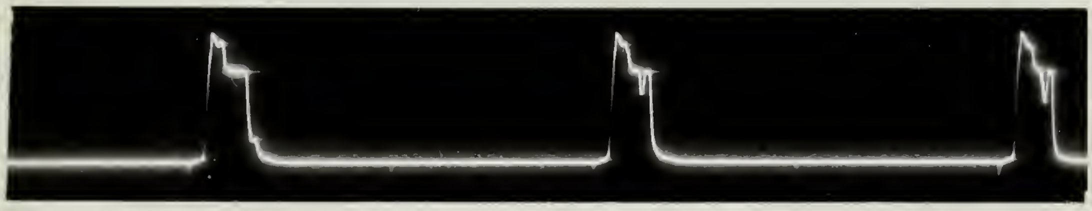


Figure 23b

Photograph of Complete Trace of the Photomultiplier Tube Output.

r	6.0	T_{oil}	140
F	0.08	RPM-23a	1000
T_i	170	RPM-23b	1400
T_j	180	Camera Speed	22 inches/second

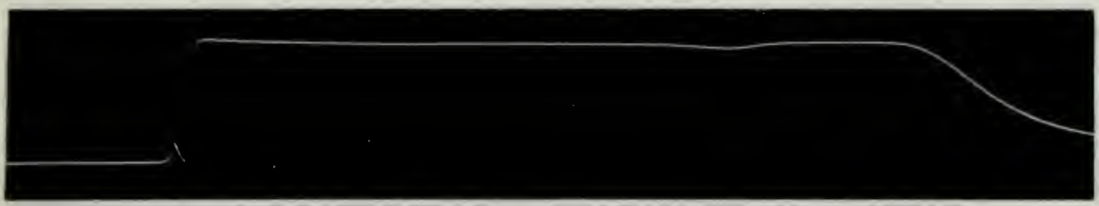


Figure 24a

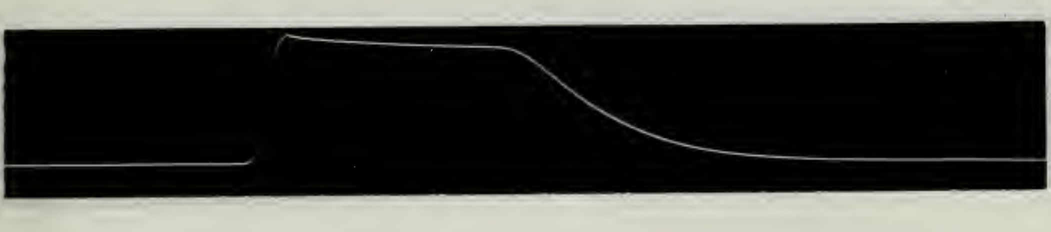


Figure 24b

Photograph of Complete Trace of the Photomultiplier Tube Output.

r	6.0	T_{oil}	140
F	0.08	RPM-24a	1000
T_i	170	RPM-24b	1400
T_j	180	Camera Speed	400 inches/second

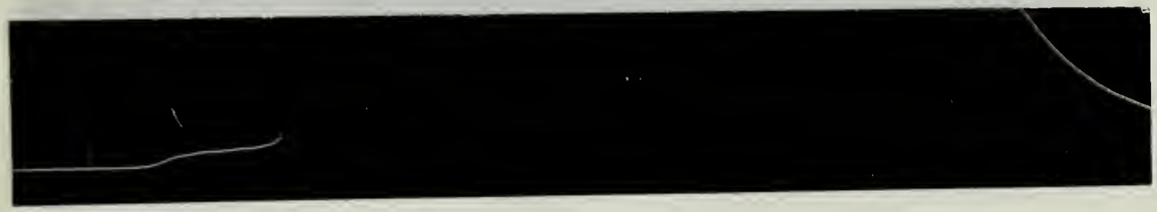


Figure 25a

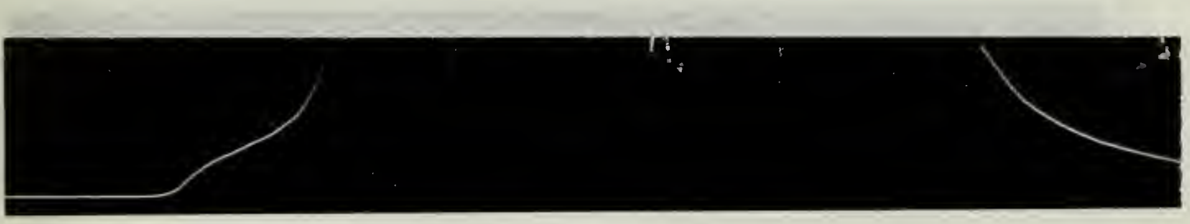


Figure 25b

Photograph of Preflame Reaction.

r	6.0	T_{oil}	140
F	0.08	RPM-25a	1000
T_i	170	RPM-25b	1400
T_j	180	Camera Speed	400 inches/second

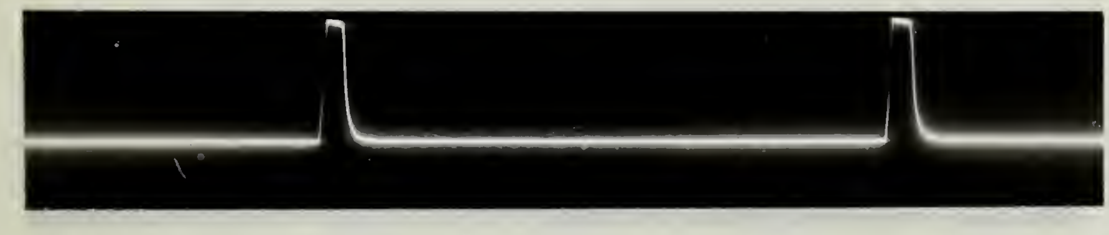


Figure 26a

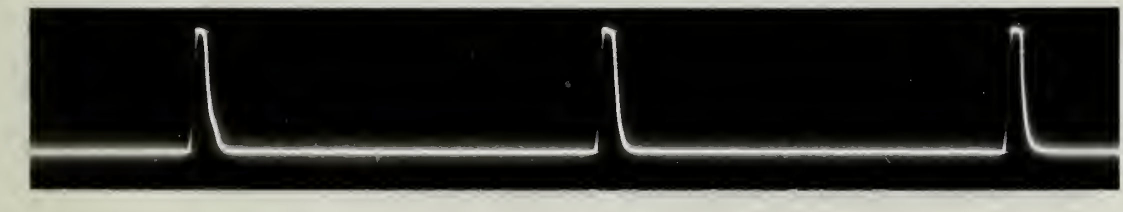


Figure 26b

Photograph of Complete Trace of the Photomultiplier Tube Output.

r	7.0	T_{oil}	140
F	0.08	RPM-26a	1000
T_i	170	RPM-26b	1400
T_j	180	Camera Speed	22 inches/second

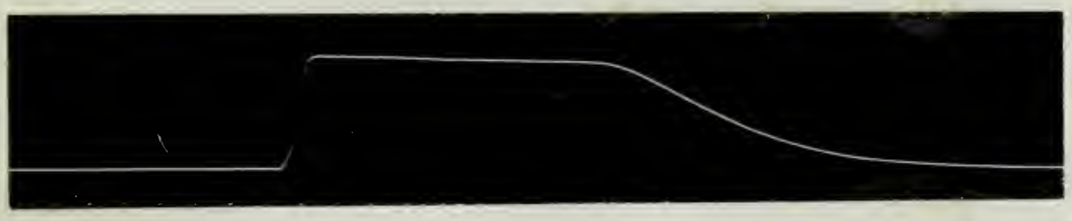


Figure 27a

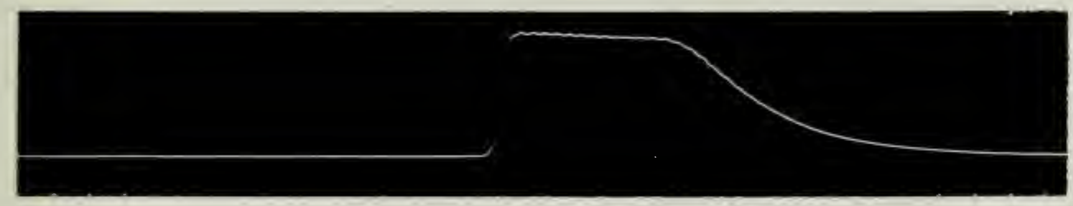


Figure 27b

Photograph of Complete Trace of the Photomultiplier Tube Output.

r	7.0	T_{oil}	140
F	0.08	RPM-27a	1000
T_i	170	RPM-27b	1400
T_j	180	Film Speed	400 inches/second

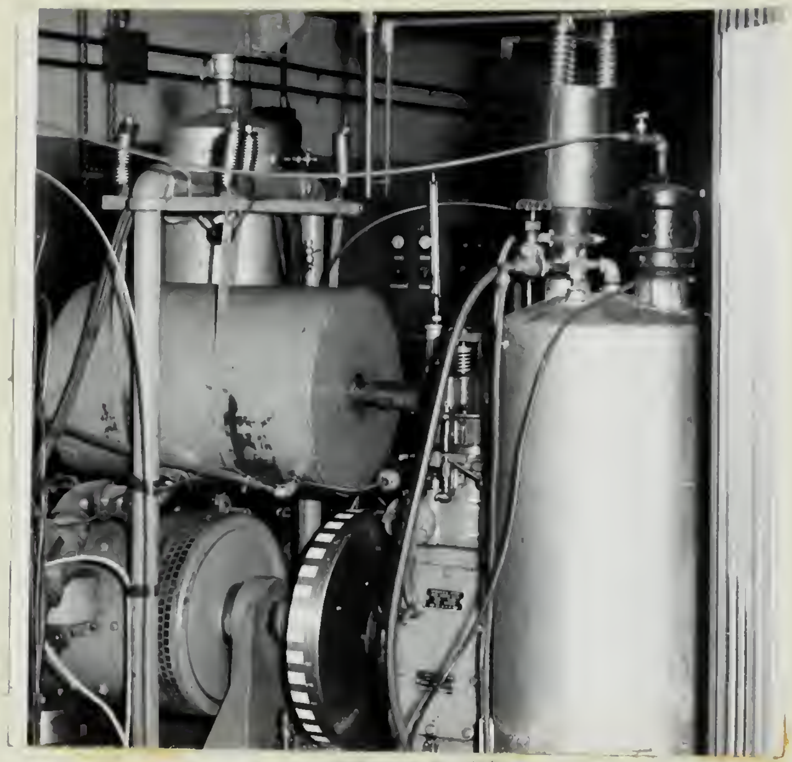


Figure 29

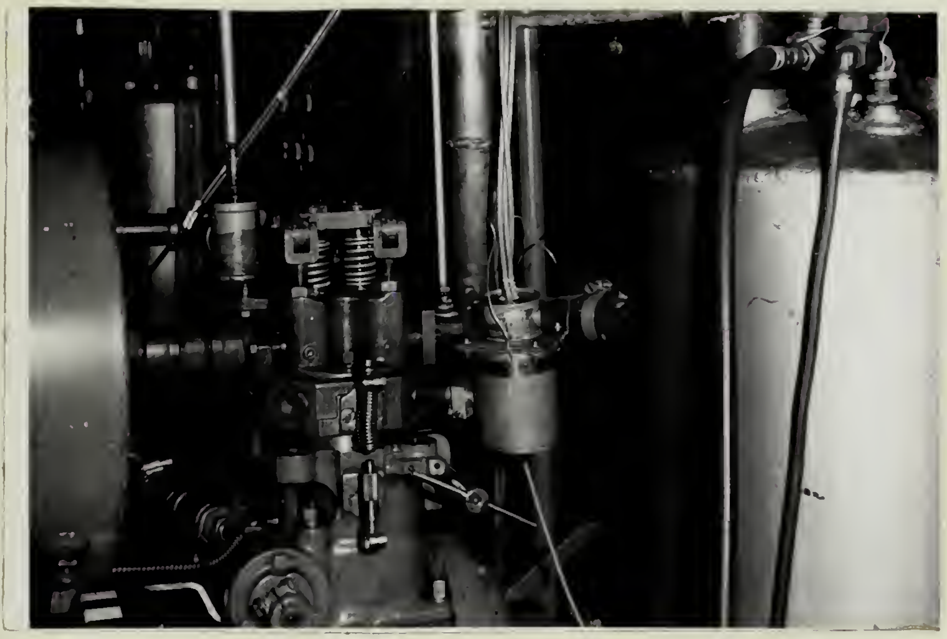


Figure 30

Photographs of Test Engine Installation

[illegible]

[illegible]

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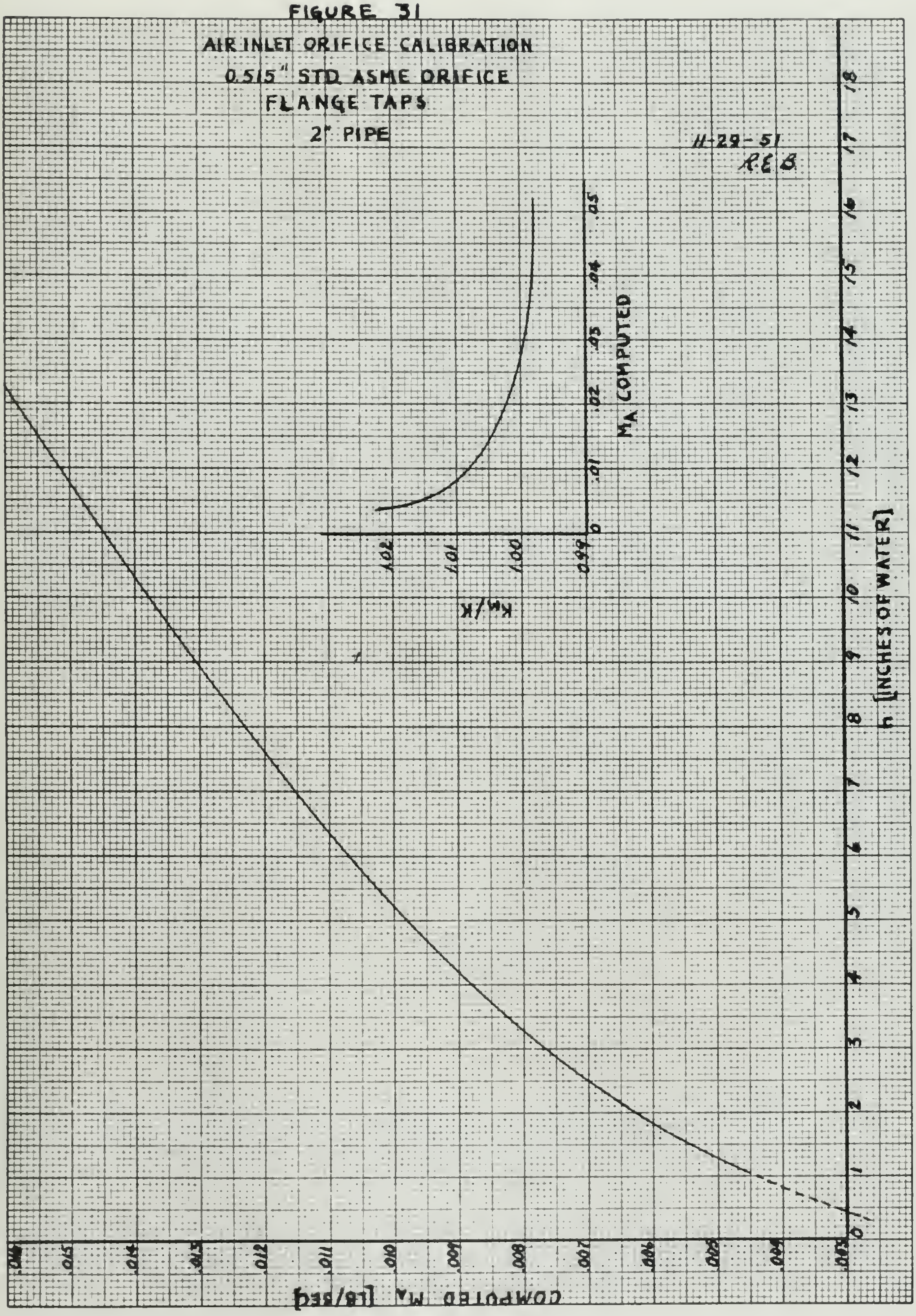

FIGURE 31

AIR INLET ORIFICE CALIBRATION

0.515" STD. ASME ORIFICE

FLANGE TAPS

2" PIPE

11-29-51

R.E.B.

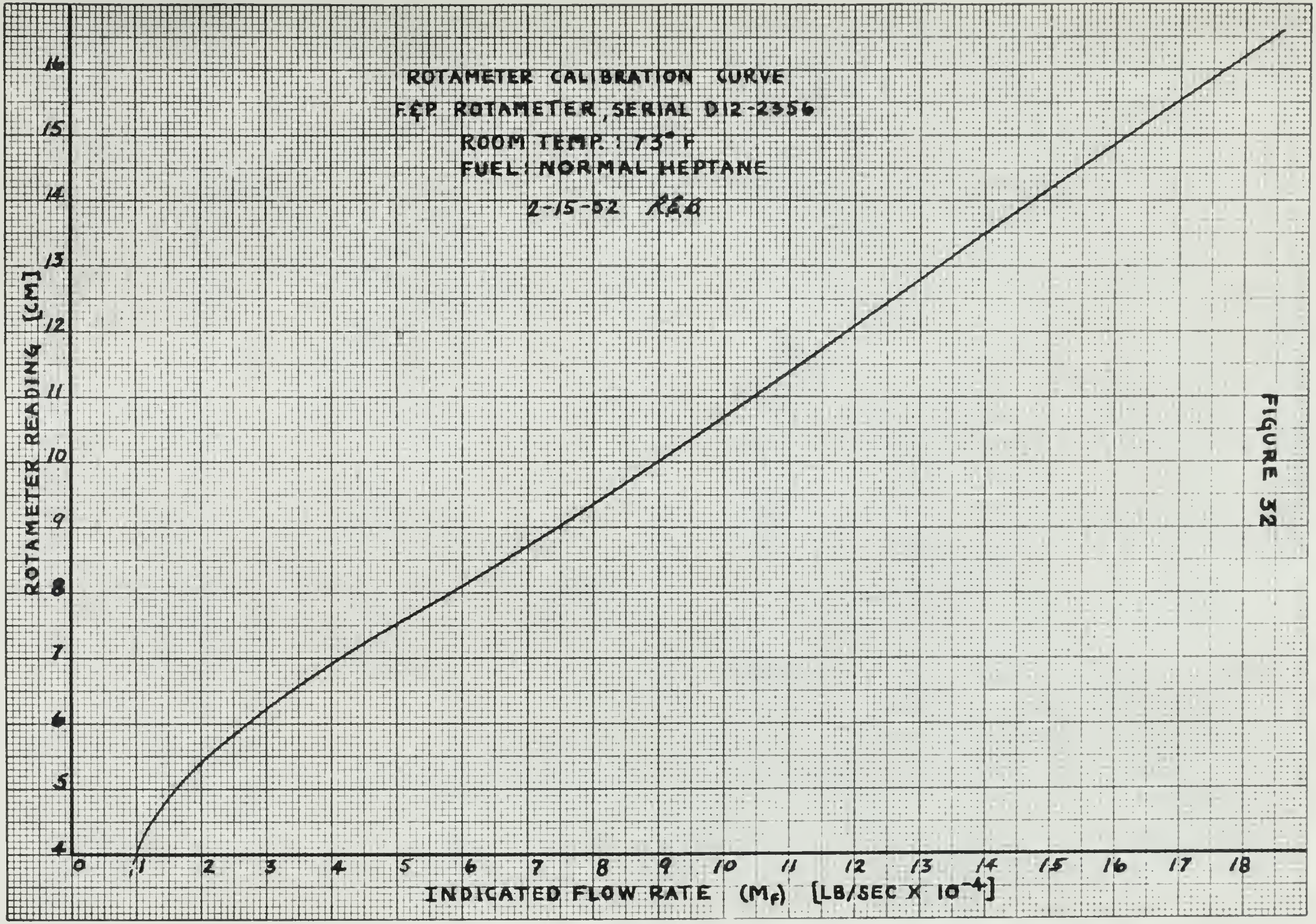

FIGURE 32

ROTAMETER CALIBRATION CURVE
F&P ROTAMETER, SERIAL D12-2356
ROOM TEMP. : 73° F
FUEL: NORMAL HEPTANE
2-15-52 REG

VIII APPENDIX

APPENDIX [illegible]

A. OPERATIONAL NOTES

One of the most difficult problems encountered in operating the engine was that of obtaining a satisfactory seal around the quartz window. Once a leak developed around the edge of the cylinder end of the window the gases from the cylinder soon eroded the edge away and made it necessary to replace the window and sealing gaskets. The best combination of sealing gaskets found by the authors was lead, copper, lead, window, lead, copper, and steel reading from the cylinder toward the phototube. When starting with a new set of gaskets, the combination was made up hand-tight and screwed into the spark plug hole in the cylinder wall. As the engine was gradually warmed up the holder was kept tight by frequently checking it with a small box wrench. During the first few minutes of firing the combination heats up and the lead and copper gaskets soften enough to make possible a good tight seal. This seal should not be broken before it is necessary to replace the window, since it is difficult to take the window out without damaging it further.

The end of the window facing the combustion chamber becomes darkened by the products of combustion after about two or three hours of operation, reducing the amount of light picked up by the phototube. This deposit was readily removed by placing the window and holder in a lathe and

polishing the window with #00 steel wool and alumina powder. So long as the window was kept reasonably clean, the preflame reaction could be picked up on the scope using -600 to -800 volts potential on the cathode of the phototube.

The socket connections and resistors of the photomultiplier tube were all covered with a good coating of coil dope to reduce leakage currents, which should not exceed 10^{-11} amperes. The complete system was entirely shielded and both ends of the shielding on all cables were connected to ground. A metal battery box was used to hold the batteries. A 10,000 ohm resistor was placed between each pair of batteries to limit the current drawn by anyone inadvertently touching the leads.

B. ORIGINAL DATA

TABLE 1. DETONATION DATA - CFR ENGINE 8B

RUN	P_i (G) IN. HG	T_i °F	T_j °F	T_{OIL} °F	ΔP "/H_2O	ROTA-METER CM.	RPM	BRAKE READING IN. HG	r	F	START OF PREFLAME REACTION °BTC	DURATION OF PREFLAME REACTION °	PHOTO FIGURE NUMBER
4-2-52	BAROMETER – 758.2 MM HG.												
1	-0.65	170	180	140	5.0	9.5	1100	28.2	5.5	.08	1	16	
2	-0.65	170	180	140	5.0	9.5	1100	28.3	6.0	.08	9	9	
3	-0.65	170	180	140	5.0	9.5	1100	26.5	6.5	.08	18	10	
4	-0.65	170	180	140	5.0	9.5	1100	23.5	7.0	.08	22	11	
5	-0.65	170	180	140	6.0	9.5	1100	22.5	7.5	.08	24	11	
6	-0.65	170	180	140	4.9	9.5	1100	21.0	8.0	.08	29	11	
7	-0.65	170	180	140	4.8	9.5	1100	20.0	8.5	.08	31	11	
8	-0.65	170	180	140	4.0	8.8	1000	20.6	8.5	.08	34	11	
9	-0.65	170	180	140	6.0	9.8	1200	19.2	8.5	.08	34	15	
10	-0.65	170	180	140	6.3	9.8	1300	19.0	8.5	.08	20*		
11	-0.65	170	180	140	7.5	10.5	1400	18.5	8.5	.08	19*		
						* DENOTES PT. OF AUTOIGNITION							
4-11-52	BAROMETER – 763 MM HG.												
12	-0.6	170	180	140	3.7	8.8	930	25.5	6.6	.08	17	8	
13	-0.6	170	180	140	4.4	9.0	1000	25.7	6.6	.08	18	9	
14	-0.7	170	180	140	5.2	9.4	1100	25.1	6.6	.08	19	10	
15	-0.8	170	180	140	6.3	9.9	1200	24.5	6.6	.08	21	11	
16	-0.9	170	180	140	7.0	10.2	1300	23.7	6.6	.08	23	12	
17	-1.0	170	180	140	8.0	10.6	1400	23.2	6.6	.08	24	14	
18	-1.1	170	180	140	8.9	11.0	1500	23.0	6.6	.08	25	15	
19	-1.15	170	180	140	9.8	11.3	1600	22.8	6.6	.08			
20	-0.6	170	180	140	4.0	8.8	950	27.7	6.0	.08	8	7	24-a
21	-0.6	170	180	140	4.4	9.0	1000	27.1	6.0	.08	12	9	23-a
22	-0.7	170	180	140	5.3	9.4	1100	27.0	6.0	.08	13	11	25-a
23	-0.8	170	180	140	6.3	9.9	1200	26.8	6.0	.08	15	12	
24	-0.9	170	180	140	7.4	10.3	1300	26.7	6.0	.08	15	13	24-b
25	-1.0	170	180	140	8.4	10.8	1400	26.5	6.0	.08	13	15	23-b
26	-1.05	170	180	140	9.3	11.1	1500	25.8	6.0	.08	14	16	25-b
27	-1.1	170	180	140	10.3	11.5	1600		6.0	.08	11	18	
28	-0.6	170	180	140	3.5	8.5	920	24.4	7.0	.08	21	9	26-a
29	-0.6	170	180	140	4.3	8.9	1000	23.9	7.0	.08	21	10	27-a
30	-0.7	170	180	140	5.1	9.3	1100	22.8	7.0	.08	23	11	28-a
31	-0.8	170	180	140	7.0	10.2	1300	22.7	7.0	.08	24	12	
32	-1.0	170	180	140	8.8	10.9	1500	21.8	7.0	.08	27	13	

TABLE 2. DETONATION DATA - CFR ENGINE 8B

RUN	P_i IN. HG (Ga)	T_i °F	T_j °F	T_{oil} °F	ΔP ''/H_2O	ROTA-METER CM.	RPM	BRAKE READING IN. HG	r	F	START OF PREFLAME REACTION ° BTC	DURATION OF PREFLAME REACTION CRANK °
4-12-52	BAROMETER - 769.4 MM. HG.											
33	-0.6	170	180	140	3.5	8.5	920	22.4	7.5	.08	25	10
34	-0.6	170	180	140	4.2	8.9	1000	21.5	7.5	.08	24	10
35	-0.7	170	180	140	5.1	9.4	1100	21.5	7.5	.08	26	11
36	-0.8	170	180	140	6.9	10.1	1300	21.0	7.5	.08	27	12
37	-0.95	170	180	140	7.8	10.5	1400	20.4	7.5	.08	28	13
	BAROMETER - 769.0 MM HG.				$M_A/N = (0.875 \times 10^{-5}) \times 2$							
38	-2.50	170	180	140	3.51	8.5	950	26.5	6.0	.08	7	10
39	-2.20	170	180	140	3.95	8.75	1000	26.0	6.0	.08	11	11
40	-2.10	170	180	140	4.81	9.2	1100	26.0	6.0	.08	12	12
41	-1.85	170	180	140	5.8	9.65	1200	26.0	6.0	.08	16	16
42	-1.80	170	180	140	6.8	10.1	1300	25.7	6.0	.08	17	16
43	-1.50	170	180	140	9.05	11.0	1500	25.0	6.0	.08	17	16
44	-1.6	184	180	140	3.51	8.5	950	26.0	6.0	.08	10	9
45	-1.6	184	180	140	3.95	8.75	1000	26.0	6.0	.08	12	11
46	-1.3	184	180	140	4.81	9.2	1100	25.7	6.0	.08	14	12
47	-1.15	184	180	140	5.8	9.65	1200	25.3	6.0	.08	17	14
48	-1.1	184	180	140	6.8	10.1	1300	25.3	6.0	.08	18	15
49	-1.0	184	180	140	9.05	11.0	1500	24.8	6.0	.08	19	17
4-25-52	BAROMETER - 767.3 MM HG.											
50	-0.6	170	180	140	4.4	9.0	1000	27.4	6.0	.08		
51	-2.0	170	180	140	3.9	8.8	1000	27.0	6.0	.08		
52	-4.0	170	180	140	3.4	8.4	1000	26.3	6.0	.08		
53	-5.0	170	180	140	3.1	8.3	1000	25.0	6.0	.08		
54	-6.0	170	180	140	2.8	8.1	1000	23.7	6.0	.08		

ENGINE STOPPED DETONATING AT P_i = -6.5 IN. HG. (Ga)

C. REFERENCES

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